CHAPTER 1

Getting the Big Picture

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Characterize analysis problems and the process used to solve them
- Characterize design problems and the process used to solve them
- Explain how the form and function of a product are interconnected
- Characterize the five phases of design
- Describe how ideas become realized as products
- Explain the economic life cycle of a product
- Explain various engineering roles in manufacturing enterprises
- Explain how and why employees are organized into functional departments
- Understand the benefits of concurrent engineering
- Realize that teamwork is essential in the workplace

1.1 INTRODUCTION

Engineering design is exciting, challenging, satisfying, and rewarding. Engineering design is exciting because we compete in world markets by engineering products such as motorcycles, airplanes, spacecraft, artificial hearts, automated assembly equipment, machine tools, and home appliances. It is challenging because we have to find solutions that are better, faster, less expensive, lighter, and safer. It is personally satisfying in that we can use our creativity to synthesize new ideas, then use our knowledge and skills in mathematics, sciences, and manufacturing to predict how well our new designs will behave before they are built. Engineering design is rewarding because we can see how our hard work leads to realization of new products that satisfy the needs of our fellow human beings.

Engineering design is a part of a bigger picture, the **product realization process** (PRP), which includes other activities such as sales, marketing, industrial design, manufacturing, production planning, distribution, service, and ultimate disposal. These activities require us to work with many different people both within and without our company. Often, we are a member of a product development team. And, as that team develops new and revised

products we make many decisions that commit the company to invest large sums of money for design, prototyping, testing, and manufacturing ramp-up. The stakes can be big because the financial and human resource investments may be substantial. The risks can be large because we may not have perfect knowledge of our markets or new technologies. And the competition may be fierce, always challenging us to develop better products in less time with fewer resources.

The main goal of this book is to help us become effective participants in the product realization process. We recognize that our main contributions to our firm are not the engineering sketches that we prepare or the computer programs we run or the engineering tests we conduct. These activities merely produce information. Rather, our primary contributions are the decisions that we make using that information. If we do our jobs well, our decisions result in successful products that satisfy our customers and produce profits to keep our company healthy.

Making decisions as a member of a team is different than making them by oneself. As a group member, we need to gain a common understanding of the design problem, alternative solutions, and ways to resolve group conflicts. This book, in essence, will examine procedures and methods that can provide us with a framework for effective, logical group-decision-making.

This chapter will first examine engineering analysis problems and differentiate them from design problems. Next, we will examine how engineering analysis is part of the overall design process. Then we will examine how engineering design is part of the manufacturing enterprise's product realization process. Finally, we will discuss product development in the context of concurrent engineering and team-based decision making.

1.2 WHAT IS ENGINEERING DESIGN?

Engineering design is the set of decision-making processes and activities used to determine the form of an object given the functions desired by the customer. Whether we are designing a component, product, system, or process, we gather and process significant amounts of information. For example, we have the task of deciding which customer needs are important, including necessary product functions and desirable product features. We try to determine desirable levels of performance and establish evaluation criteria with which we can compare the merits of alternative designs. We consider the technical, economic, safety, social, or regulatory constraints that may restrict our choices. We use our creative abilities to synthesize alternative designs incorporating varied shapes, configurations, sizes, materials of composition, or different manufacturing processes.

We utilize knowledge and methods from the basic sciences, mathematics, and engineering sciences to predict or simulate the performance of each alternative before it is built, thereby avoiding the time and expense of tinkering. We thereby consider how alternative "**forms**" influence each alternative's "**functions**," as shown in Figure 1.1. And we communicate our decisions as a

Form ever follows function

Form is intimately connected to function. As the famous architect Louis Sullivan once said, "Form ever follows function." The form of an object, in other words, usually depends upon the function it will perform. Consider a screwdriver for example. Its tip has a shape that drives the screw into the hole. The handle is configured to conform to the human hand, permitting the application of torque and thrust. The injection molding process used to make the handle permits cost-effective manufacture. Finally, the steel shank material safely transmits the torque and thrust from the handle to the tip.

The function of a product is what the product is expected to perform. Basic functions include: control, hold, move, protect, and store. We use verbs to characterize functions. We use the term "behavior" to describe how the product actually performs. Form, on the other hand, is what the product looks like, what materials it is made of, and how it is made. We use nouns to characterize the form of a product. Form characteristics include: shape, size, configuration, material, and manufacturing processes used to make the product.

The essence of design is to determine a form to satisfy the required function, as shown in Figure 1.1.

Function	Control Hold Move Protect Store
↓	
Design	Decision making processes
↓	
Form	Shape Configuration Size Materials Manufacturing processes

the character of design problems and discussing a simplified model of the design process. We also discuss an example shaft design problem to illustrate the five phases of design.

1.2.1 Engineering Analysis

Analysis problems have a number of characteristics in common. Consider the following "analysis" problems:

- Given an object of mass m, with applied force, E, we determine its تسارع acceleration a, using Newton's second law of motion $a = F/m$.
- Given the cross-section geometry of an aluminum airplane wing, we determine the lift it produces by conducting wind tunnel experiments.
- Given the diameter and height of a welded, cylindrical tank, we calculate its volume and surface area using simple geometry relations.
- Given a cast steel engine block drawing, we estimate its weight.

In each of these examples we are given some information about an object and then asked to predict its "behavior." Having studied the basic sciences and mathematics, we are familiar with how things work and can model behavior as a function of input data. For example, we can model an object's acceleration (the predicted behavior) according to $a = F/m$ (an analytical equation), which, of course, depends upon the mass (form) and force (input data). Moreover, if we lack an equation, we might be able to conduct a number of engineering experiments to develop an empirical relation. Note too, that for analysis problems, the given information usually pertains to the form of an object such as shapes, configurations, sizes, material compositions, and or manufacturing processes. Therefore, when solving an *analysis* problem we *predict the behavior* or function of an object, based on its given form, using analytical equations or experimental methods.

> Predicted behavior is the solution to an analysis problem.

To help us better understand the differences between the analysis process and the design process let's examine the analysis problem-solving process in detail. The analysis process can be further described as having three main stages: formulating, solving, and checking.

Formulating As we formulate an analysis problem we are essentially trying to understand the problem and plan its solution. After gathering related information, we might draw a sketch or diagram using an approximate scale for lengths and angles. We would show pertinent geometry (shapes, dimensions, and angles) and illustrate the relevant physics, such as mechanical forces and moments. We would record all the "given" information and state what we are to "find." Next we would recall related problems that we had modeled in the

past, listing appropriate principles and formulas. We might even break up the problem into smaller subproblems. We would then transform or interpret our problem into the model we knew how to solve, noting any and all assumptions between our "real" problem and the "ideal" model. At this point in the problem-solving process, we have a pretty good understanding of the problem and a set of modeling equations. We prepare a rough plan how to solve the equations whether by calculator, computer, or even analog experiments.

Solving During this stage we logically try to determine the unknown(s) by solving an equation, or system of equations, using standard mathematical methods. We systematically set up the equations observing appropriate units and conversions. We verify that the number of unknowns is less than, or equal to, the number of equations. We might start by solving an equation that has more known quantities than unknowns, substituting our results into succeeding equations. Assuming that the equations are solvable, we find our solution and label it along with appropriate units.

Checking During checking we examine the validity, accuracy, and precision of our solution. We also interpret our solution to determine whether it "makes sense." Does it violate laws of nature or mathematics? We evaluate the answer with regard to the number of significant digits of precision. We might also solve the problem using an alternative method such as a graphical technique or computer simulation. Typically, the independent solution methods give similar results, unless we did something wrong in our calculations or made a wrong assumption. In other words, there is usually just one answer to an analysis problem. We reread the initial problem to assure that we really answered the problem.

1.2.2 Engineering Design

Design problems, however, differ from analysis problems. Consider the following "design" problems.

- Determine a rope-and-pulley combination including materials, sizes, and methods of construction given that the customer desires to manually lift a 500-pound engine block three feet above a given truck frame.
- Select a satisfactory pump-and-motor combination given that the customer desires to pump fuel oil from a 5,000-gallon storage tank to a boiler.
- Determine the shape and size of a storage tank given that the customer desires to store 350 gallons of gasoline,
- Develop a product given that the customer desires to fry eggs.
- Select appropriate sizes for a bolt, nut, and washer given that the customer desires to fasten two steel plates together.

In the examples above, we are asked to determine the form given information relating to the desired function. For example, we are to find the form of the

rope-and-pulley combination (pulley size and type, rope materials and size, configuration of pulley block, whether the pulley is welded or cast, and so on) given the required function, that is to "lift" engine block.

As in an analysis problem, we need to process input information. However, note that in a design problem the "given" information is often fuzzy or ill-defined. For example, in the toaster design problem: how many slices of toast, how dark, what types of bread? In most design problems we usually do "problem finding" before we do "problem solving." Design problems are also "open-ended." Since there are many possible design alternatives that can provide the desired function, we see that design problems generally have more than one "solution."

Design problems involve consensus building and group decision making such as in determining customer needs and evaluation criteria. Unlike the routine simultaneous solution of a system of equations in an analysis problem, there are few, if any, structured procedures to follow that will guarantee a "solution." Design problems are therefore said to be ill-structured as well as open-ended.

Form is the solution to a design problem.

How does solving a design problem differ from solving an analysis problem? Let's look at a simplified model of the process used to solve design problems and compare it to the analysis process. We recognize that each business may use different decision-making methods or procedures that are tailored to its company or trade. The simplified model shown in Figure 1.2, however, incorporates four essential stages: formulate, generate, analyze, and evaluate.

Formulating As we formulate a design problem we try to understand the problem and plan its solution. We gather information about the customer such as necessary product functions, acceptable levels of performance, and desirable performance targets. We also try to determine relevant constraints regarding economic, ergonomic, technical, legal, and/or safety considerations. Most important, we record our findings as detailed engineering design specifications to help guide our future decisions. We develop a design project plan to coordinate "what" tasks will be completed by "whom" on our team and "when." In other words, **formulating** is the set of activities and decision-making processes used to understand a design problem and prepare a plan for its solution.

Generating During this stage we synthesize, or generate alternative designs that might satisfy the customer. We might use creative methods such as brainstorming and Synectics to arrive at an initial concept design, then develop it into a layout or configuration, each alternative "form" having different shapes,

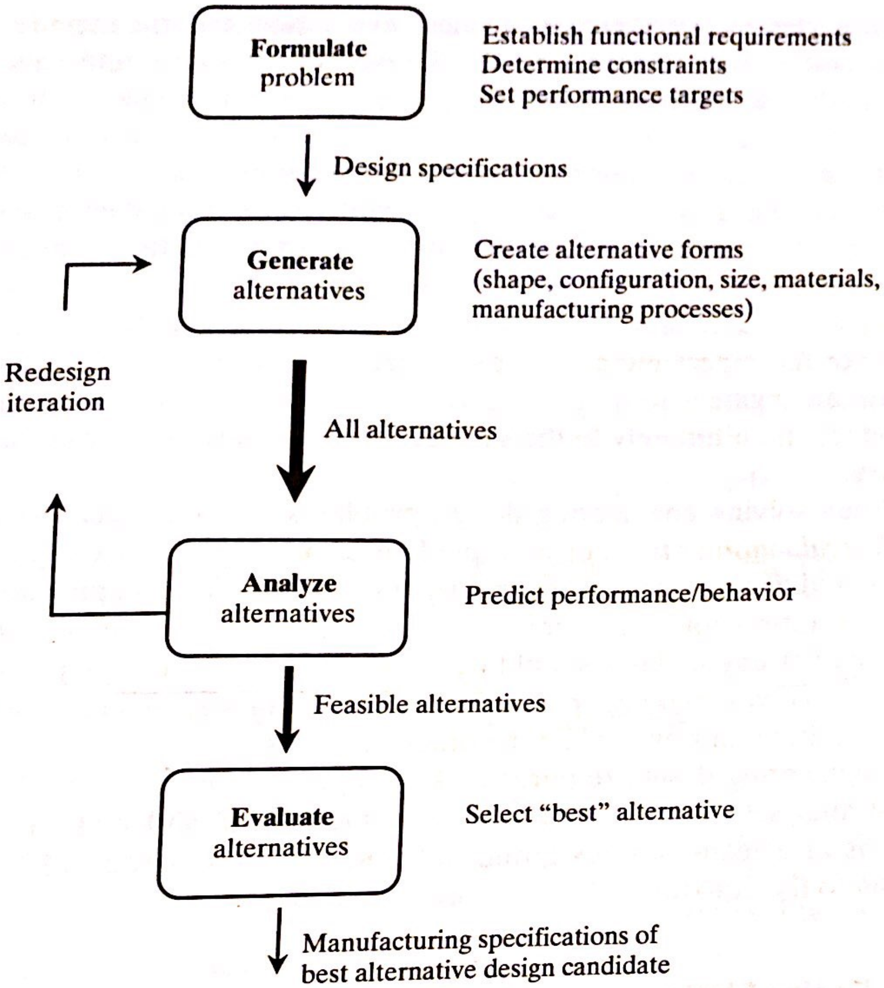


FIGURE 1.2 The essential stages of the design include formulate, generate, analyze, and evaluate.

configurations, sizes, materials, or made with different manufacturing processes. **Generating** is the set of activities and decision-making processes used to create alternative design candidates for later analysis and evaluation.

Analyzing is the process of predicting the performance or behavior of a design candidate. Using knowledge from the basic sciences and computational skill from mathematics, we prepare engineering models to predict the performance of each design alternative. The candidate designs that fail to satisfy the constraints are reiterated. That is, new values of "form" are chosen and the redesigned candidate is reanalyzed. If no feasible candidates can be found, the problem may be over-constrained and may need to be respecified to relax some of the constraints. Redesign is shown as the solid reiteration loop in Figure 1.2.

Evaluating is the process of comparing the predicted performance of each feasible design candidate to determine the "best" design alternative. The merit of each design candidate is estimated using evaluation criteria laid out in the

engineering design specification. Typical evaluation criteria include performance measures such as speed, size, reliability, maintenance intervals, power, weight, and cost. Also, optimal design methods, employing computerized numerical techniques, can be used in some cases to automatically regenerate new candidate designs to improve expected performance and overall quality.

Perhaps the most significant aspect about engineering design, compared to engineering analysis, is that engineering design includes analysis! All engineering design activities relate to developing the best product to satisfy customer needs. Design is the reason why we do what we do. Analysis is just one part of the bigger picture. In particular, the reason why a manufacturing firm pays an engineer to do analysis is because it contributes to the quality of the product and ultimately to the satisfaction of the customer, who really pays his salary.

When solving engineering design problems we often have to deal with *multiple evaluation criteria*, or multiple figures of merit. For example, our customer would like a stronger, heavy-duty transmission for his application. But a stronger transmission is heavier and more expensive. Which is more important, cost or strength? How should we decide? Like most design problems, this example involves making *trade-offs*, or compromises, wherein one performance attribute improves while the other degrades.

Engineering design requires making *logical decisions* in addition to numerical analyses. Since a product development team will make many of the decisions as a team, various group decision-making methods will be used in addition to the equation solving we use for analysis.

1.2.3 Design Phases

A product design evolves over time in **design phases** from the identification of a customer need to the realization of the finished product. Let's examine the following situation:

> Our customer owns and operates a custom-built machine tool used in her factory. The tool has a drive shaft that can only be stopped by turning off the power and waiting about 90 seconds for the shaft to spin-down. The customer considers this a safety hazard and would like to actuate some device that would bring the shaft to a quicker stop. The shaft is 8 inches in diameter, weighs 1,000 pounds, is made of 4330 steel, and spins at 3,000 rpm. We have been hired to design and fabricate a solution to accomplish the rapid stopping of the shaft.

1. Initially, we explore the stated customer need and develop a list of objective design specifications. For example, we obtain details of the existing shaft geometry and operating conditions in the factory, including available power. Additionally, we try to clarify the type of performance that would satisfy the customer. For example, how quickly should the shaft stop? Would the customer be fully satisfied with 5 seconds and unsatisfied if longer than 20 seconds? We might do some simple calculations, using simple relations from

physics, to better understand the overall mechanical forces and/or torques of the system. Our activities in this initial phase focus largely on problem *formulation*. In other words, we are not trying to solve the problem, merely understand it.

2. During the **concept design** phase we synthesize a variety of candidate working principles or concepts and their abstract embodiments. For example, we might consider the following three alternative concepts:

a. air friction as the working principle and fan blades as the embodiment,
b. opposing magnetic fields as the working principle and an electric generator as the embodiment, and
c. surface friction as the working principle and a disk-and-caliper brake as the embodiment.

Then, after developing a list of evaluation criteria, we select one of the concepts for further development.

3. Then, we generate a variety of configurations including the arrangement of individual components. For example, if during concept design we select a disk-and-caliper brake, during configuration design we consider alternative shaft locations, and geometries for the disk and caliper. **Configuration design**, therefore, is the design phase when alternative configurations are generated, analyzed, and evaluated.

4. During the **parametric design** phase, we determine values for the controllable parameters, called design variables, identified as unknown during the configuration phase. Design variables deal with the form of a design, that is, its shape, configuration, size, material, and manufacturing process. For example, we determine specific values for: rotor diameter (outer), rotor thickness, and brake pad width. We also select pad material type, operating pressure of the hydraulic piston, and rotor manufacturing processes. Then, we analyze the performance using conventional machine design formulas, computer programs, or physical experiments. We check the analysis results to assure that all the constraints are satisfied and that an optimal performance is obtained. If not, we *iterate*, or **redesign** by generating new candidate designs with new values for the design variables. Then we reanalyze, evaluate, and so on.

5. During the **detail design** phase, we determine the remaining product specifications such as the surface finish, pad bonding resin, and assembly procedures. We might also fabricate and test a number of critical parts. We also prepare a complete package of *manufacturing specifications* including detail and assembly drawings, bill of materials, manufacturing process recommendations, prototype performance test results, and product specifications such as height, width, depth, weight, expected performance.

A number of terms are used in industry and academia to describe various groupings of design phases. For example, *preliminary design* is often referred to the *collection of activities* relating to concept design, configuration design, and parametric design. Also, *embodiment design* refers to design activities relating to configuration design and parametric design activities.

Engineering design researchers have proposed similar models of the design phases. Pahl and Beitz (1996) proposed four phases including: (1) task clarification, (2) concept design, (3) embodiment design, and (4) detail design. Dixon and Poli (1995) presented a model that splits embodiment design into configuration and parametric design phases. Dieter (2000) included product architecture as an additional phase before configuration design.

In this text, we will closely examine a five-phase model as proposed in Figure 1.3. The five phases include: (1) formulation, (2) concept design, (3) configuration design, (4) parametric design, and (5) detail design. The only difference between the proposed model and Dixon and Poli's model is that formulation is defined as an explicit and crucial phase of design.

Engineering design and product development, in general, rarely proceed through all phases of design in a systematic, linear fashion as described in Figure 1.3. For example, revisions to products may need only parametric and detail design work, while a new technological breakthrough may require configuration, parametric, and detail design efforts. In another case, a candidate concept design may be found to be unmanufacturable during configuration design thereby requiring concept re-design.

Product development teams that generally follow the five phases of design benefit in three major ways:

1. *The teams focus on the right subproblem at the right time.* For example, team members will not be trying to establish machining tolerances during concept design, when the part dimensions are not even known. Or, in another case, alternative configuration design candidates will not be evaluated before the evaluation criteria are established during formulation.
2. *The teams efficiently gather and process the right type of information.* In formulation, for example, customer needs are typically abstract and ill-defined, as compared to parametric design when more specific information is necessary.
3. *The teams focus on alternative methods pertinent to the phase.* For example, a variety of creative methods can be explored during concept design. In another case, we might investigate alternative CAD software packages during parametric design.

1.3 HOW DOES ENGINEERING DESIGN FIT INTO THE PRODUCT REALIZATION PROCESS?

In the previous sections we examined how engineering design activities translate customer needs into product manufacturing specifications. But, how are manufacturing specifications turned into real products? Are we finished with our work once we "turn over" the manufacturing specifications? Are the manufacturing specifications ever really finished?

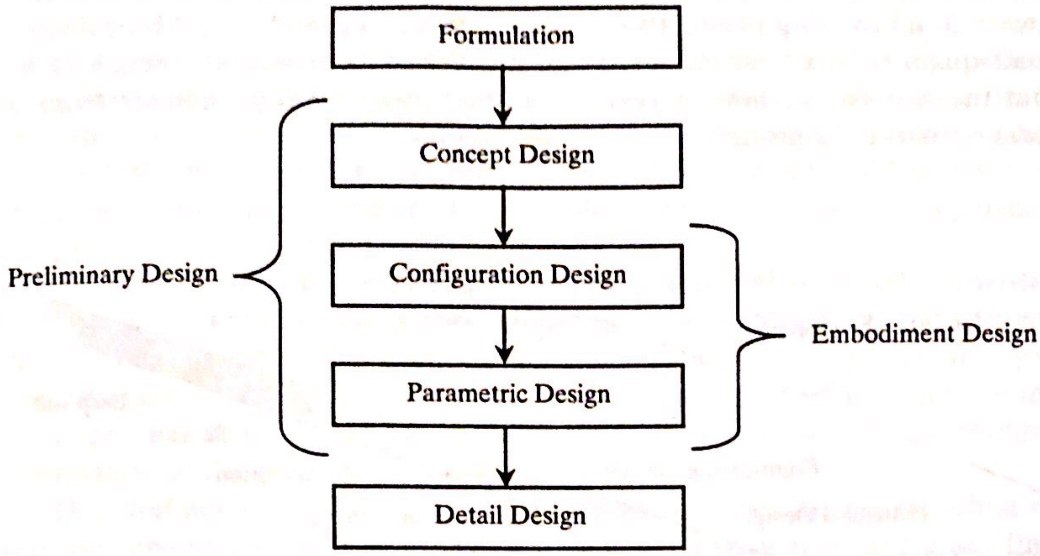


FIGURE 1.3 Five phases of design, emphasizing the crucial nature of design problem formulation.

We recognize that most parts and components are mass-produced in today's modern design and manufacturing environment. As a consequence, parts must be made to be interchangeable with each other. We accomplish interchangeability and mass production using intricate systems composed of people, procedures, and machinery. Even when only a few products are "manufactured," as in the production of a nuclear-powered aircraft carrier, we use similar systems involving many people, systematic procedures, and expensive machinery.

Successful design teams work on tasks appropriate to the design phase.

In the next sections we will consider how engineering design is an important part of the product realization process and how a product contributes to the life of the business enterprise.

1.3.1 Product Realization Process: The Big Picture

The product realization process is the means by which a customer need is transformed into a realized product. Alternatively, Dixon and Poli define the product realization process as a complex set of interrelated activities, both cognitive and physical, involving the whole firm, by which new and modified products are conceived, produced, brought to market, serviced, and disposed of. The process involves physical activities and decision-making activities (cognitive), involving sales, marketing, industrial design, engineering design, production design, manufacturing, distribution, service, and disposal, as shown in Figure 1.4.

A customer need for a new or improved product can originate from almost anywhere in the firm. Often the service department is the first to become aware of an existing product's shortcomings. For example, we might discover inadequate product packaging during distribution shipments to retail outlets. But the majority of new or revised product ideas usually originate from the *sales* or *marketing* groups.

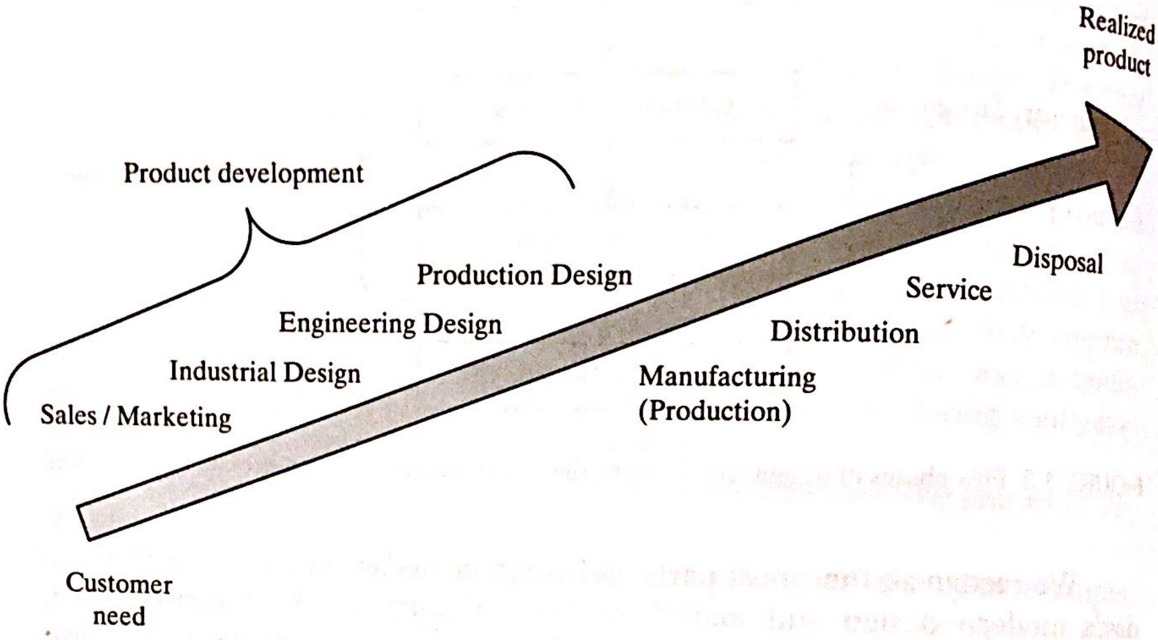


FIGURE 1.4 The product realization process is the means by which a customer need is transformed into a realized product (adapted from Dixon and Poli).

Industrial design activities focus on how the new or revised product idea is compatible with the customer's anatomical limitations and/or aesthetic trends in the marketplace. Often the industrial design group will prepare an artistic rendering or a physical model that illustrates basic product form, color, texture, and intended functionality.

Engineering design activities result in recommended manufacturing specifications that satisfy the customer's functional performance requirements and manufacturing constraints.

Production design activities involve the design, fabrication, and installation of production equipment such as jigs, fixtures, machine tools, quality control instrumentation, and material-handling equipment. In some cases, it might involve the construction of a new factory. Production design also considers the design of manual and automated assembly equipment. Even as the first units come off the production lines, the production design group may be making changes to reduce material waste and rework.

Manufacturing activities relate to fabrication, assembly, and testing. They also include training, scheduling, and supervising production employees. Significant coordination between engineering design, production planning, and manufacturing is necessary during ramp-up as bugs in the product design and

manufacturing processes are worked out. Others sometimes describe "Manufacturing" as *all* the activities of a manufacturing enterprise, often referred to as the big "M." Note that in this text manufacturing will be defined as fabrication, assembly, and testing, usually referred to as the little "m" manufacturing.

Distribution activities involve shipping the product in wholesale-sized lots to distribution centers located around the country or world. In some cases, railcar-full shipments are packed. Most often, containerized freight trailers are used. Some companies ship directly to retailers or the customer, as in personal-computer mail ordering.

Service activities for consumer products usually relate to maintenance, repair or replacement at the factory. However, large appliance manufacturers will train repair persons for home service such as washing machine or dryer repair. For some industrial products such as commercial refrigeration systems, service persons actually do the equipment installation, as well as routine maintenance, at the customer's site.

Disposal activities involve the removal, elimination, and/or recycling of hazardous chemicals or scarce materials such as in nuclear power plant fuel rods, automotive oil, or printer cartridge recycling.

Indirectly, the product realization process involves administrative activities such as accounting, finance, personnel, strategic planning, legal, and management. These behind-the-scenes activities help to coordinate the whole organization and their costs are often referred to as *indirect expenses*.

We refer to **product development** as the collection of activities leading up to, but not including, production. Therefore, we can see that product development is more than engineering design. It also involves post design activities such as production planning and the coordination of activities relating to ramping-up of production. Even after the product is launched into the market, engineering design may be involved in making minor improvements for improved performance, safety, or cost reasons.

We can aggregate some of the decisions made by the various departments and explicitly incorporate how the customer will "use" the product. This results in a simplified model of the product realization process having four main stages that represent the whole life of a product: design, manufacture, use, and retire, as shown in Figure 1.5. As we look over the four stages let's take special note of what engineering fields are involved.

Early in the life of a product, sales engineers, applications engineers, field service engineers, and others identify customer needs. This information leads to new product ideas, which are subsequently developed into mature product designs by industrial designers, design engineers, materials engineers, and test engineers as they determine the form of the new product.

Then, industrial, manufacturing, and quality engineers convert the design into a final product for manufacture. During this phase they plan, organize, and fabricate new tooling and fixtures. They also construct facilities and equipment to assemble and distribute the product.

Upon delivery, the consumer receives and sets up the product. This typically involves unpacking, cleaning, and in some cases assembling components.

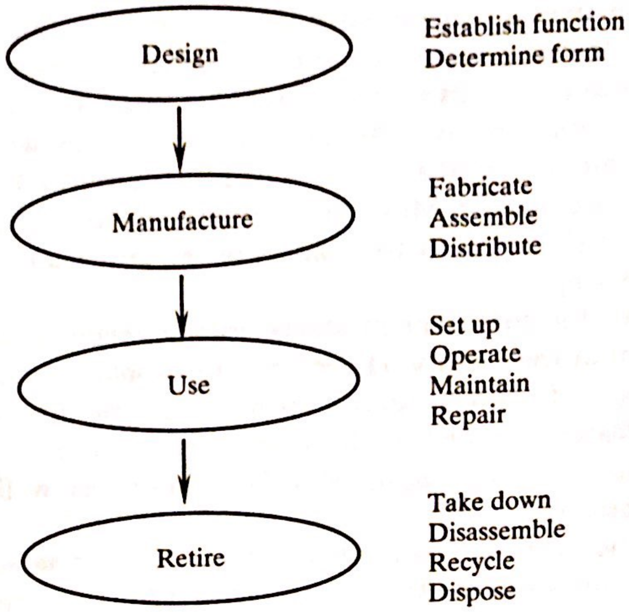


FIGURE 1.5 The four stages in the life of a product include design, manufacture, use and retire.

During and after operation, the product is *maintained* by cleaning, lubricating, and adjusting. If necessary, the product is repaired by replacing worn or broken parts. Field service engineers are sometimes responsible for installation, maintenance, and repair activities for large or complex industrial and commercial products.

Once the product is retired, it is removed from service, disconnected, and relocated. Large assemblies are taken down and disassembled into smaller, more manageable units. Materials are recycled when possible. Non-recyclable parts are disposed of.

Thus, we can conclude that engineering design is just one part of the big picture, called the product realization process that involves many departments and employees during the life of a product.

1.3.2 Economic Life Cycle of a Product

A business will typically devote significant financial and manpower resources to the development of a new product, as shown in Figure 1.6. Unlike annual operating expenses, product development expenditures are usually considered long-term investments. Furthermore, the business will expect to receive returns on that investment over the economic life of the product.

Initially, as the product is introduced to the market, its sales begin to grow slowly (Crawford and DiBenedetto, 2003). As more and more customers learn about the product, sales begin to increase during a *growth phase*. Then, at *maturity*, sales income levels off. Once the market is *saturated*, few new sales occur and sales income *declines*.

The time over which these phases occur can be years or months. The basic hammer, for example, has been around more than a hundred years. In some cases, technological improvements make a product obsolete, as in the case of the beta-format video recorder. Products live and die because conditions change, customer preferences change, technologies change, regulations change, and material costs and availability change.

As a product declines, the business will have a new product to take its place, as shown by the dashed line in Figure 1.6. The "birth" and ultimate "death" of a product is often called the **product life cycle**. Thus, as one product approaches maturity a new product emerges from product development. Successful companies usually have many new product ideas in various stages of development, such that their annual volumes continue to increase each year.

1.4 THE MANUFACTURING ENTERPRISE

As we learned from the product realization process and the economic life of a product, significant resources both human and financial are involved. A couple of questions naturally come to mind, such as, who is entrusted with the resources of the enterprise to make the right decisions? Or, how does a business enterprise coordinate the decisions made by so many employees?

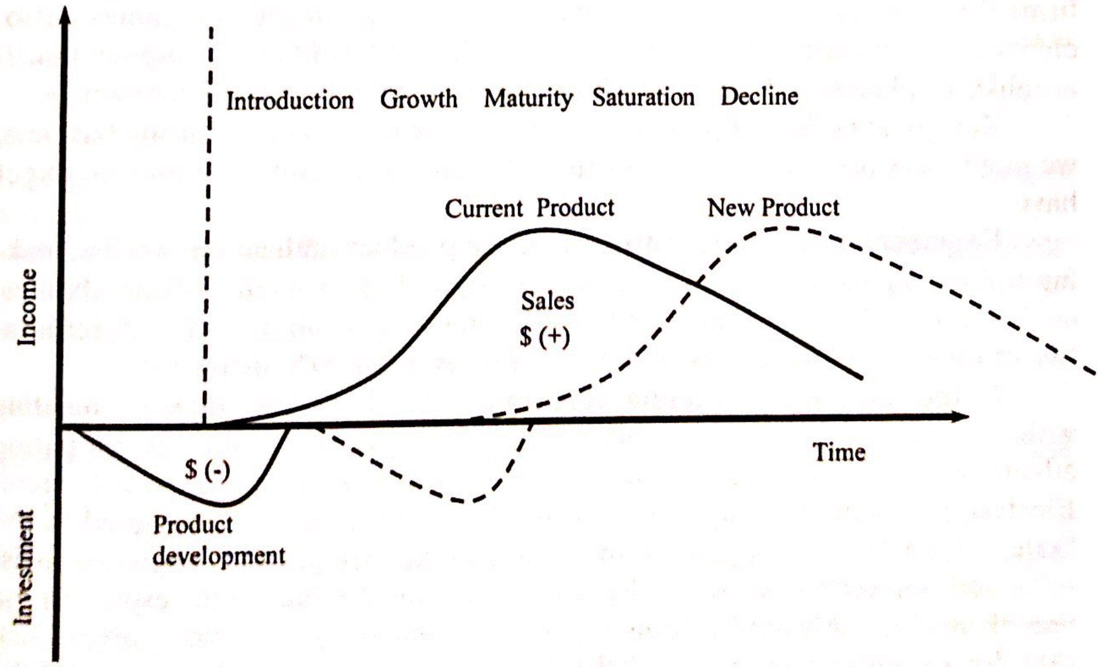


FIGURE 1.6 Economic life cycle of a product. As the current product declines, a new product is introduced and thereby keeps the company healthy.

In the next sections we will examine the various roles that engineers play in the product realization process, how a manufacturing enterprise is organized into an effective structure, and how modern product development practice makes use of the concurrent engineering approach.

1.4.1 Engineering Roles

Manufacturing employment directly accounts for a large portion of the engineering jobs in the United States. The Bureau of Labor Statistics reported that engineers held about 1.5 million jobs in 2006.

> About 37 percent of engineering jobs were found in manufacturing industries and another 28 percent were in the professional, scientific, and technical services sector, primarily in architectural, engineering, and related services. Many engineers also worked in the construction, telecommunications, and wholesale trade industries.
>
> Federal, State, and local governments employed about 12 percent of engineers. About half of these were in the Federal Government, mainly in the U.S. Departments of Defense, Transportation, Agriculture, Interior, and Energy, and in the National Aeronautics and Space Administration. Most engineers in State and local government agencies worked in highway and public works departments (U.S. Department of Labor, 2006).

Note that when engineers are working directly for a non-manufacturing business, they often interact with manufacturing businesses, providing engineering services or purchasing their goods. For example, engineering-service firms often design systems and facilities for manufacturing companies. Also, engineers in government positions will specify and purchase equipment such as tanks, airplanes, and ships, which are made by manufacturing companies.

Recognizing that we will be working in or with a manufacturing business, we might now ask ourselves about the roles and responsibilities that we might have.

Engineers are deployed throughout the product realization process, making full use of their technical, mathematical, and/or problem-solving abilities, as shown in Table 1.1. Note that the titles and responsibilities are representative of those used in industry and do not represent an exhaustive list.

In the sales and marketing department we find *sales engineers* meeting with customers, determining needs, presenting product offerings, preparing advertising campaigns, negotiating terms of sale, and closing the sale. General Electric, for example, may have two or three sales engineers assigned to the "sale" of a \$100 million gas turbine power plant. *Applications engineers* assist sales and marketing personnel by solving technical issues with respect to the use of product. An applications engineer assigned to a turbine power plant sale, for example, would investigate its operating costs and benefits, and the integration of the plant with the customer's site. *Field service engineers* are usually responsible for installing, maintaining, and repairing equipment, often at customer sites.

In the research and development department we often find industrial designers, design engineers, materials engineers, and test engineers. *Industrial designers* establish the essential product appearance as it relates to human factors and aesthetic concerns. *Design engineers* translate the function desired by the customer into part or product form including: shape, size, configuration, materials, and manufacturing processes. *Materials engineers* investigate and develops improved materials. *Test engineers* are responsible for designing and conducting performance and safety tests at various stages in the product development.

In the manufacturing department we often employ industrial engineers, manufacturing engineers, and quality control engineers. *Industrial engineers* are usually responsible for designing fabrication, assembly, and warehousing systems. They try to optimize the system of workers, machines, and materials handling. *Manufacturing engineers* develop manufacturing tools and fixtures used to fabricate and assemble parts. *Quality control engineers* establish and maintain instrumentation and documentation systems to control the quality of raw materials and finished goods.

Table 1.1 Engineering roles in the product realization process.

Department / Function	Job Title	Responsibilities
Sales and marketing	Sales engineer	Meets customers, determines needs, presents product offerings, negotiates terms of sale
	Applications engineer	Assists sales & marketing solving technical issues with respect to the use of product
	Filed service engineer	Installs, maintains and repairs equipment at customers' sites
Research and Development	Industrial designer	Establishes essential product appearance, human factors
	Design engineer	Decides part or product form including: shape, size, configuration, materials, and manufacturing processes
	Materials engineer	Investigates and develops new materials
	Test engineer	Designs and conducts performance and safety tests
Manufacturing	Industrial engineer	Designs fabrication, assembly and warehousing systems
	Manufacturing engineer	Develops manufacturing tools and fixtures
	Quality control engineer	Establishes and maintains raw materials and finished goods quality controls
Processing / operations	Plant engineer	Designs and maintains processing plant facilities
Miscellaneous	Project engineer	Coordinates project work tasks, budgets and schedules

In processing companies we find plant engineers and project engineers. *Plant engineers* design and maintain processing plant facilities. For example, a chemical plant producing thermoplastic polymers may have $500 million invested in pumps, tanks, chemical reactors, boilers, and piping. In addition to making improvements from time to time, the plant engineers are responsible for keeping the plant operating 24 hours a day, seven days a week.

Project engineers coordinate project work tasks, budgets, and schedules. Projects are commissioned to complete a variety of activities, including new equipment installations, new product development, the design of a new factory, and replacement of automated assembly equipment.

1.4.2 Organization

Most manufacturing enterprises are formed as a corporation owned by stockholders. Stockholders provide most of the funds that a business uses to purchase land, buildings, equipment, and other assets for its operations. Stockholders elect the board of directors to oversee the activities of the president and other officers of the company. The board of directors provides advice to the president and officers regarding broad policies and long-term strategies, while the president, as chief executive officer and as principal trustee for the stockholders, has the responsibility and authority to make day-to-day decisions committing financial and human resources.

An example **organization chart** is shown in Figure 1.7. In this example, the president's chain of command includes five subordinate managers responsible for specific functions of the business. These positions often carry the title of vice president or manager.

Businesses organize their employees according to their specialized functions called departments, such as: sales, marketing, finance, purchasing, manufacturing, and research and development. Employees in the same department perform similar types of work. Consequently, the department manager can be most effective in hiring, training, developing, and supervising his or her employees. A company's **organization structure** establishes areas of responsibility and authority facilitating the management of employees and coordination of its operations (Badiro and Pulat, 1995).

Businesses also *process* raw materials or agricultural products such as iron ore to steel, steel ingots to sheet metal, petroleum to plastics, potatoes to French fries, or cattle to beef products. These businesses also organize their operations into similar *specialized functions* that facilitate the nature of their business, as shown in Figure 1.7.

Since different businesses may have more or less departments, employees, and/or managers, we find many variations of the basic organization presented in Figures 1.7 and 1.8.

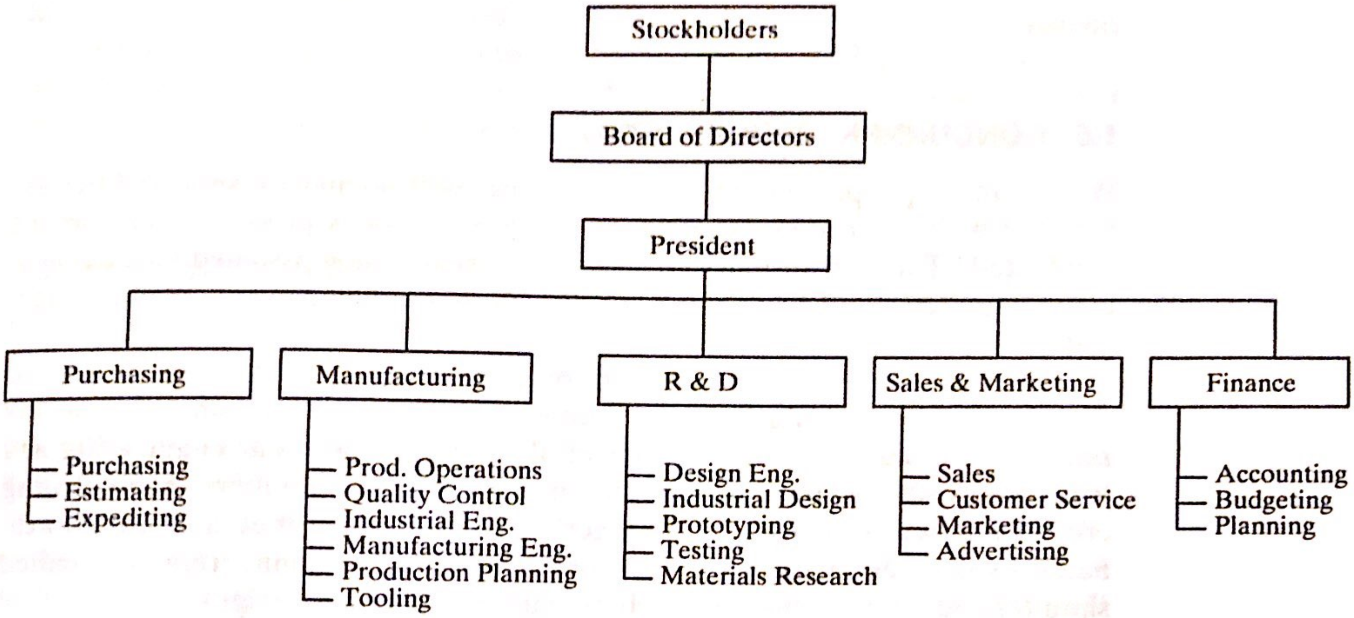
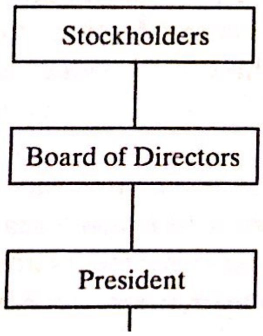


FIGURE 1.7 Functional organization chart of a typical manufacturing company.



would be the combining of manufacturing activities with research and development activities. Another example would be the grouping of purchasing with finance.

1.5 CONCURRENT ENGINEERING

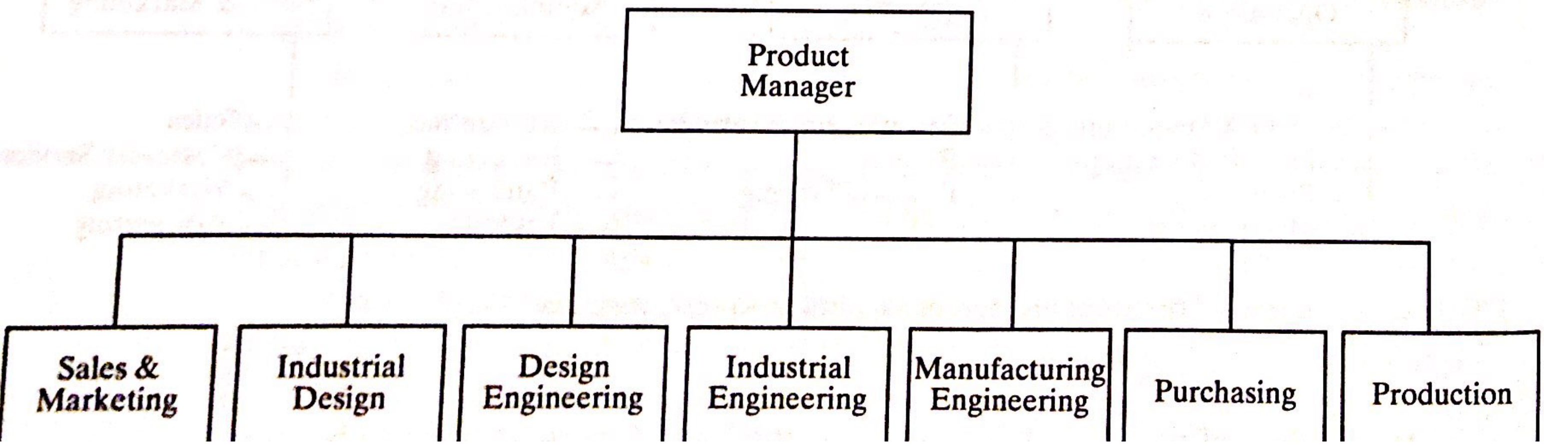
With so many people in the typical enterprise, with so many responsibilities associated with the product realization process… how is product development conducted? The best product development occurs when assigned to a team of employees representing the various functions or departments of the enterprise.

Modern product development practice takes advantage of increased communication, coordination, and employee motivation by using the concurrent engineering approach (Wesner et al., 1995). **Concurrent engineering** is a team approach to product design, in which team members, representing critical business functions, work together in the same office and are coordinated by one senior manager. The aim of concurrent engineering, also called simultaneous engineering, is to achieve superior product designs.

Prior to concurrent engineering, customer requirements information was usually forwarded to the design group without follow-up. Product design specifications were prepared and then handed over to the manufacturing group for production. Little interaction occurred during product development, leading to many miscommunications and production delays. This approach is referred to as "over the wall" product development.

An example of a concurrent engineering product development team is shown in Figure 1.9. A concurrent engineering team is composed of members representing the primary business functions. We call this cross-pollinating mix of team members a *cross-functional* team composition.

Concurrent engineering teams are usually *collocated* (Carter and Stilwell-Baker, 1992). Placing team members next to each other in the same office area



increases the quantity and quality of communication. Members also tend to develop a sense of teamwork, loyalty, and camaraderie.

Concurrent engineering teams are also *coordinated*. A product development manager, at a high level in the organization structure, has sufficient authority and responsibility to make timely decisions and commit resources effectively.

1.6 TEAMWORK IN PRODUCT REALIZATION

Many people, including employees, consultants, customers, and vendors, contribute to the realization of a new or revised product. We appreciate that we cannot design, manufacture, and distribute mass-produced products by ourselves. We work with a "team" of employees who make up the company and appreciate that teamwork is essential for successful product realization.

Companies involved in product realization are similar to teams in professional sports. Let's examine the characteristics of professional teams, such as professional football teams. Then, we can extend the analogy to suggest ways in which we might improve the teamwork within our own company. It is worth noting that companies often hire distinguished coaches to present in-plant seminars on improving teamwork.

Competitors, Companies, and Customers. Professional teams compete against one another with the primary goal of winning games for the pleasure of their paying customers. Companies compete against one another attempting to satisfy customer needs with the goal of earning profits for their investors.

Owners and Investors. Professional teams and businesses are owned by individuals or corporations that provide the initial funds to set up and operate the franchise or business. Owners and investors expect to receive some returns on their investments in the form of dividends or increases in equity.

Professional Players, Employees, and Teams. In both businesses and professional team sports, the participants are paid professionals. Employees and players are members of the big leagues and earn professional salaries and bonuses. As they join the serious ranks of a professional team, professional players leave behind the jovial, friendly game of "touch football." Similarly, as a member of a department, project, or product development team, we have serious roles and responsibilities to perform. The competition is exciting and the job is challenging.

Coaches and Managers. Professional team coaches select, guide, and direct their players. Managers hire, train, and supervise employees in the performance of their duties. Coaches and managers also provide strategic advice, expertise, and direction to guide their teams on the competitive playing field.

Referees, Umpires, Lawyers, and Judges. Professional team sports have rules that are enforced by referees or umpires. Manufacturing enterprises are regulated by codes, standards, and other local, state, and federal laws that are enforced by lawyers and judges.

Communication and Coordination. Coaches and players communicate during the game. Signals are spoken clearly and loudly so that every player knows the specific actions he or she is to take. As we have often seen on television, games can be lost by players who "miss the call." Communication is similarly essential in business so that everyone in the product realization process knows what to do, when to do it, and how to do it. Therefore, in addition to being skillful in the modes of communication, we must also know the terminology used in product realization.

Fumbles, Injuries, Risk, and Uncertainty. Competition and product realization is filled with uncertainty, such as weather changing the playing conditions or new regulatory laws changing competitive conditions. A player can drop or fumble the ball, as well as get injured on the field. Employees can similarly make mistakes or get injured on the job. A certain amount of risk is inevitable in both cases. Imperfect knowledge and risk are just part of business and sports and must be accommodated. Decisions need to be made and actions need to be taken. Note, however, that successful teams plan for and prepare to overcome these difficulties.

Individual Skills. Winning players are *good at the position they play*. Initially, they prepare themselves in physical training such as weight lifting, jogging, sprinting, and other physical exercises, to develop individual abilities of speed and strength. Then they learn and memorize all the "plays" that the team may execute during a game. Then during practices, they hone and coordinate their physical abilities with knowledge of the plays, to improve execution and timing. Similarly, successful employees recognize the importance of individual contributions to their department, project, or product development team. Initially they prepare themselves by developing technical knowledge and skills in the basic sciences, mathematics, engineering sciences, manufacturing processes, and design. They gain experience in design methods, computational tools, prototyping, and testing. They develop communication skills for effective listening, speaking, reading, interpreting, writing, sketching, and drawing. They learn and use "the jargon." They develop a professional interpersonal "style" embracing empathy, tolerance, honesty, trust, and personal integrity.

Team Skills. Winning teams have outstanding players and coaches. They routinely practice offensive and defensive plays, so that they can flawlessly execute them during games. They also have effective, alternative, and adaptive game strategies. If our company is to be successful, we need to have outstanding employees and managers. We need to know and fulfill our roles and responsibilities well. We need to adopt sound alterna-

CHAPTER 2

Defining and Solving Design Problems

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Characterize different types of design problems
- Describe product and process plant components
- Decompose and diagram a product's components
- Characterize types of design
- Select and apply design problem solution strategies

2.1 INTRODUCTION

What characteristics distinguish one design problem from another? Let's consider the following design problem examples.

Longer-life lightbulbs. Our R&D department indicates that a newly developed material will extend the life of the current product by 20 percent. Should we modify our existing product line?

Safer toaster. Our customer service department reports that many customers have complained about toaster oven, model #453, blowing circuit breakers in their home wiring. Is a manufacturing defect the cause or is a new design required to fix the problem? Is it ethical to continue shipping the existing toaster ovens without fixing the problem?

Lower-emissions lawn mower. Due to new Environmental Protection Agency regulations, we must select a new engine for our current product line of power lawn mowers. What factors will we consider?

Lightweight canoe paddle. Marketing studies indicate that our current line of solid wood paddles is too heavy for the growing market of young paddlers. Should we invest in the development of a new paddle using lighter materials?

Special-duty robot welder. The U.S. Navy has contacted our company to design and manufacture a new remotely controlled underwater welding robot.

If only six units are ordered, what manufacturing processes would be economical?

Fewer broken potato chips. We have been asked to redesign our company's packaging equipment to reduce the number of broken potato chips per bag. Can a modification to the existing equipment fix the problem?

Lower-cost car seat. Our customer, a leading automobile manufacturer, has contacted our company to lower the total cost of a line of passenger seats that we make for them. What compromises will our customer be willing to make? Cost for comfort? Cost for safety?

We readily see that some design problems involve *improvements* to existing products, such as the lightbulb and car seat. Others require the development of a new product, something that never existed before, such as the robot welder. A **design problem**, therefore, can be defined as a product/process deficiency that needs resolution, or a product/process opportunity that needs consideration.

Some design problems involve relatively simple, *one-piece products*, shaped from a single material such as a toothpick or baseball bat. Others, such as an automobile and a commercial jet airplane are examples of very *complex products* that include thousands of components made with different materials or manufacturing processes.

Some design problems deal with knowing the difference between the *customer* and the *consumer*. For example, redesigned car seats are bought by the customer and then sold to the consumers who actually use them. Will satisfying the customer's desire for a lower cost be acceptable to the consumers if it means a trade-off in comfort or safety?

Technology readiness is also used to characterize design problem types (Ulrich and Eppinger, 1995). Although R&D may have developed a new light bulb filament material in the laboratory, is it manufacturable in the factory? Will the new technology be cost-effective? Will it work reliably?

Finally, design problems can also involve different quantities of production, such as the mass-produced toothpick or the one-of-a-kind machine to package potato-chips.

In the remainder of this chapter, we describe the basic anatomy of products and process plants to establish a nomenclature of component and process terminology. We then use the new terms to examine strategies for solving design problems.

2.2 PRODUCT AND PROCESS PLANT ANATOMY

Products are made of one or more fundamental components arranged in structured assemblies. Process plants, factories, and facilities are also designed to function with multiple components. Products and process plants have structures, like the parts and systems of the human body that work together. Much like medical students, we can benefit from the study of the "anatomy" of products and process plants as presented in sections 2.2.1 and 2.2.2.

2.2.1 Product Anatomy

A **product** is an item that is purchased and used as a unit (Dixon and Poli, 1995). Table 2.1 lists a small portion of the many thousands of products manufactured each year. Note that each item listed can be purchased and used as is. In other words, no further fabrication or assembly is typically required.

TABLE 2.1 Example Products

army helicopter	milling machine
automobile	paper clip
bag of potato chips	paper cup
baseball bat	penlight
bicycle	portable CD player
canoe paddle	power lawn mower
carton of milk	refrigerator
coffee maker	garage door opener
commercial jet	steam boiler
fishing reel	toaster oven
incandescent light bulb	toothpick
inflatable kayak	vacuum cleaner
laser printer	welding robot
leaf rake	wrench

Some products are simple and others are complex depending on the *number, type, and function of their components*. For example, the paper clip, canoe paddle, and toothpick are single-component products. The penlight, bicycle, and toaster oven are somewhat more complex. The refrigerator, automobile, and commercial jet airplane are very complex.

Products are composed of components that include parts and assemblies. A **part** is a single piece requiring no assembly. It is sometimes called a **piece-part**. An **assembly** is a collection of two or more parts or subassemblies. A **subassembly** is an assembly that is incorporated into another assembly or

TABLE 2.2 Examples of Each Type of Product Component

Standard parts	Standard assemblies	Special purpose parts
bolt	pump	equipment housing
nut	valve	access cover
washer	electric motor	control link
rivet	clutch	support bracket
shaft key	chain	washing machine tub
gasket	heat exchanger	automobile windshield
v-belt	brake caliper	hood ornament
gear blank	ball bearing	motorcycle fender
shear pin	power screw	flashlight case
lubricant	gasoline engines	
sprocket	electric switches	

Example

Decompose the penlight shown in Figure 2.1 into its constituent components. Identify whether the components are parts or assemblies and in particular whether they are standard or special purpose. Then prepare a product component decomposition diagram to illustrate the basic anatomy of the penlight.

Looking at the assembly drawing from left to right, we see that the penlight is an assembly of a cap, bulb, battery, spring, button switch, and case. The cap is a special purpose part made specifically to hold the bulb. The bulb is a subassembly composed of a glass lens, filament, and base. Since the bulb is mass-produced and made in standard sizes it is a standard subassembly. The spring is a part that is usually purchased as a standard part. The special-purpose button part acts as a switch by pushing the battery toward the bulb to connect the circuit. The battery is a standard subassembly including an anode, cathode, electrolyte paste, and plastic cover. The metal case is a special-purpose part, cylindrical in shape and electrically conducting.

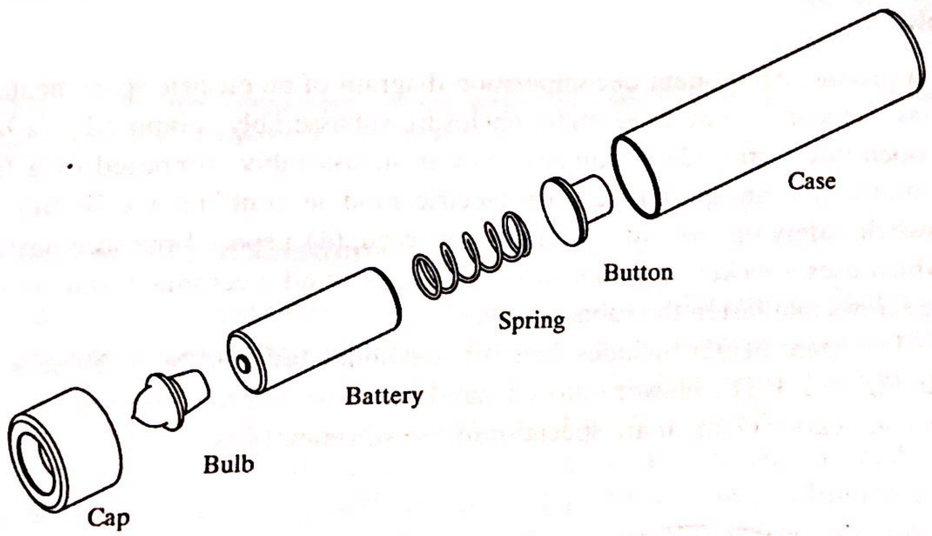


FIGURE 2.1 Assembly drawing of penlight showing standard and special-purpose components.

A product component decomposition diagram is shown in Figure 2.2. Note that the diagramming scheme uses an oval to represent a product and a rectangle for a subassembly. Individual parts are shown as plain text. Also note that solid lines, joining the components, are used to show the hierarchy of the parts and subassemblies.

The decomposition diagram readily illustrates that the product is an assembly of two subassemblies and four parts. We note that the function of the bulb is to convert electricity to light. The function of the battery is to store electrical energy, and the case supports the components as well as conduct electricity from the battery to the bulb.

The decomposition reveals that the penlight assembly depends upon selecting and purchasing standard components such as the bulb, battery, and spring. It also depends on the sound design and fabrication of the special cap, case, and button, each of which will necessitate decisions regarding appropriate materials and manufacturing processes.

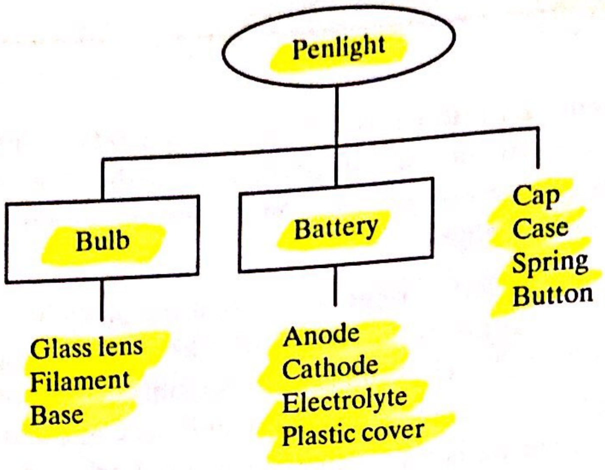


FIGURE 2.2 Product component decomposition diagram of a penlight.

Example

Prepare a product component decomposition diagram of an electric space heater. The heater has: (1) a special-purpose metal enclosure subassembly composed of a housing and an open-faced grill, (2) a standard blower subassembly composed of a fan and electric motor, (3) an special purpose electric module containing a blower switch, heater switch, safety tip-over switch, and power cord, (4) a special-purpose heating element, which uses a nickel cadmium wire wrapped around a ceramic frame and (5) six machine screws that fasten the subassemblies.

The space heater includes four subassemblies fastened by machine screws as shown in Figure 2.3. The blower unit is a standard subassembly. The enclosure, control module, and heating element are special-purpose subassemblies.

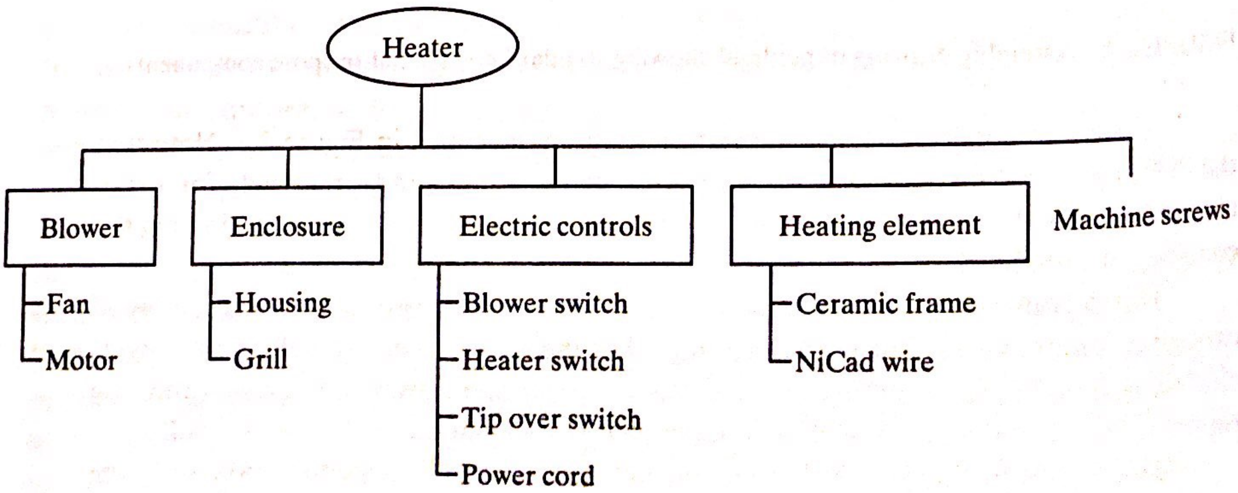


FIGURE 2.3 Component decomposition diagram of an electric heater.

In general, a product can be decomposed into its components including subassemblies or parts, which may be standard or special-purpose in nature, as shown in Figure 2.4.

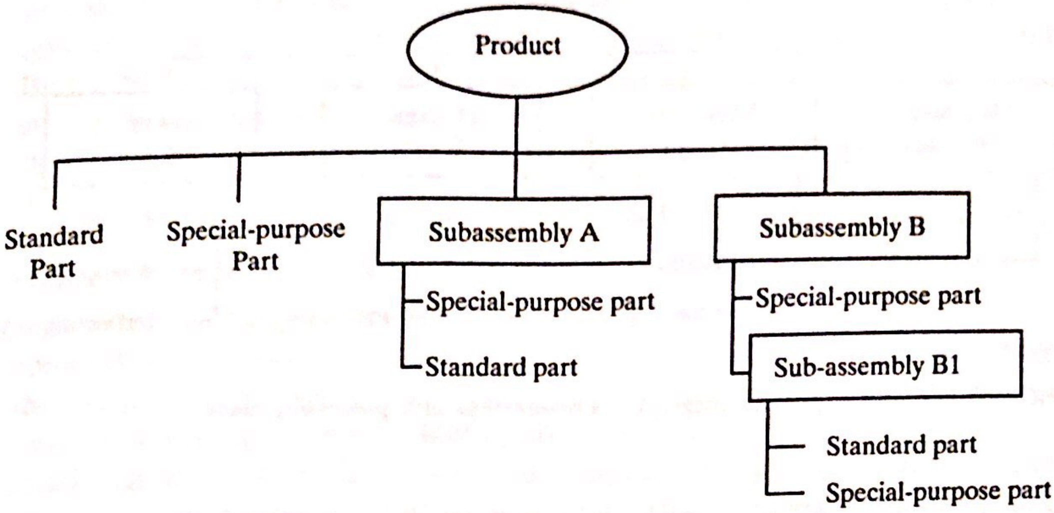


FIGURE 2.4 Product component decomposition diagram of a product having parts and sub-assemblies, both standard and special-purpose.

2.2.2 Process Plant Anatomy

Design engineers sometimes design process plants. Examples include: meat and vegetable processing, iron ore processing, petroleum plants, stamping plants, hydroelectric power plants, and steel plants. A **process plant** is a combination of systems used to process energy or materials (both organic and inorganic). A process plant is usually a one-of-a-kind design, customized to meet specific needs. A frozen-vegetable processing plant is shown in Figure 2.5.

The plant includes four systems: washing, blanching, freezing, and packaging. A **system** is two or more pieces of equipment used to perform a set of processes. Other system examples include: waste treatment, auxiliary power generation, materials handling, HVAC.

Each system is composed of pieces of equipment that perform simpler specialized processes. To **process** means to mechanically or chemically treat matter so as to change its properties. Examples include: refrigerating, heating, separating, distilling, refining, spraying, chilling, evaporating, melting, homogenizing, freezing, heat-treating, cleaning, inspecting, and sorting.

Equipment refers to machines or apparatus designed to perform a process or portion thereof. Examples include: feed water pumps, boilers, condensers, electroplating tanks, and paint sprayers.

In general, a process plant is an integrated arrangement of systems, and pieces of equipment, as shown in Figure 2.6.

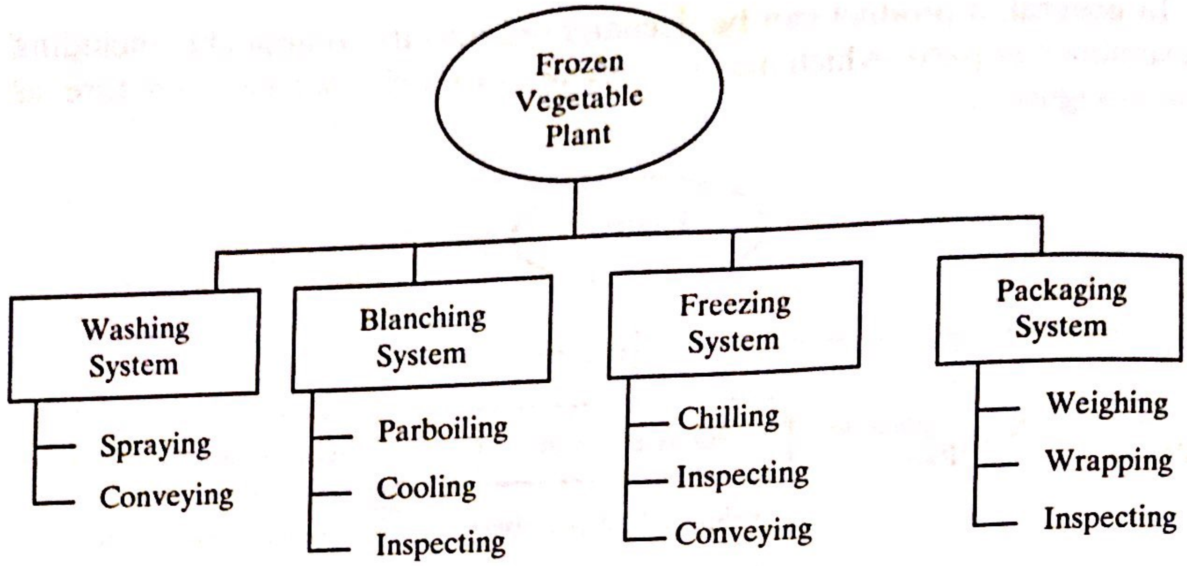


FIGURE 2.5 Decomposition diagram of a frozen-vegetable processing plant.

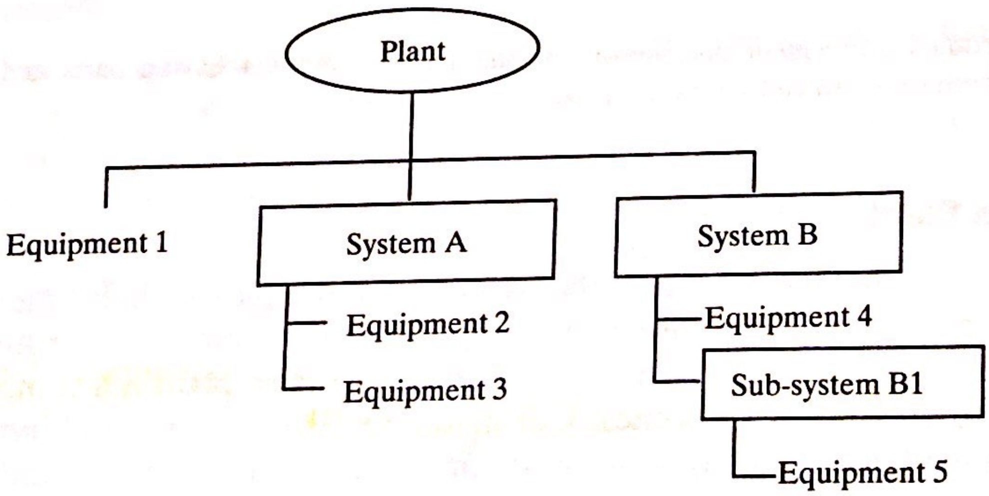


FIGURE 2.6 Decomposition diagram of a process plant.

System design methods ≈ Product design methods

Although this book will usually refer to product design, the design methods and techniques presented are commonly used to design systems and process plants.

nomenclature and anatomy of products and process plants is used to describe the following types of design.

Variant Design. **Variant design** seeks to modify the performance of an existing product by varying some of its design variable values or product parameters such as size, or specific material, or manufacturing processes (Pahl and Beitz, 1996). Examples would include: modifying the length of a lever to increase mechanical advantage, or using aluminum for a part rather than steel to reduce weight, or using die casting rather than sand casting to reduce processing costs. Note, however, that the fundamental working principle or concept is usually maintained. For example, the size of the gasoline engine is revised rather than exchanged for an electric motor.

Adaptive Design. **Adaptive design** is when we adapt a known solution to accomplish a new task. Examples of adaptive design would include: adapting the ink-jet printer concept to spray a glue to bind powders in layers as a rapid prototyping method, adapting the cell phone concept to include personal digital assistant functions, and adapting the positive displacement pump concept in reverse to be used as an internal combustion engine (Pahl and Beitz, 1996).

Original Design. **Original design** refers to conceiving and embodying an original, innovative concept for a given task (Pahl and Beitz, 1996). Ullman (1997) describes original design as the development of a new component, assembly, or process that had not existed before.

Selection Design. In **selection design** we match the desired functional requirements of a component with the actual performance of standard components listed in vendors' catalogs. For example, if we were designing a belt-and-pulley drive, we would determine the belt type and size, or the pulley shaft-bearing types and sizes. Or, if we were designing a new lawn tractor, we would have selection design problems relating to the size and type of gasoline engine or the size and type of wheels.

Part, Assembly, Product Design. Design may be characterized with respect to whether a part, assembly, or product is being designed. For example, the following types of design generally increase in component complexity: standard part design, special-purpose part design, standard assembly design, special-purpose assembly design, and product design.

Concept Design, Configuration Design, Parametric Design, Detail Design. Design may also be characterized by the timing and type of information being processed, as in the design phases such as: formulation, concept design, configuration design, parametric design, or detail design. Configuration design of a special-purpose part, for example, requires determining the number, type, and approximate arrangement of geometric features, whereas concept design of a prime mover would examine alternative working principles such as electric motors, steam engines, or gasoline engines.

Redesign. Much of our working career will be devoted to the improvement of existing products. To obtain the improvements we usually modify parts, or

subassemblies, or combinations thereof, by changing their shapes, sizes, configurations, materials, and manufacturing processes. Since design is determining "form," whenever we improve an aspect of form we are essentially redesigning.

Artistic Design. **Artistic design** deals with an object's appearance, such as "designer" clothing or furniture. Since engineering design calls for the application of science and mathematics to predict the behavior of a candidate design before it is made, artistic design is not engineering design, however.

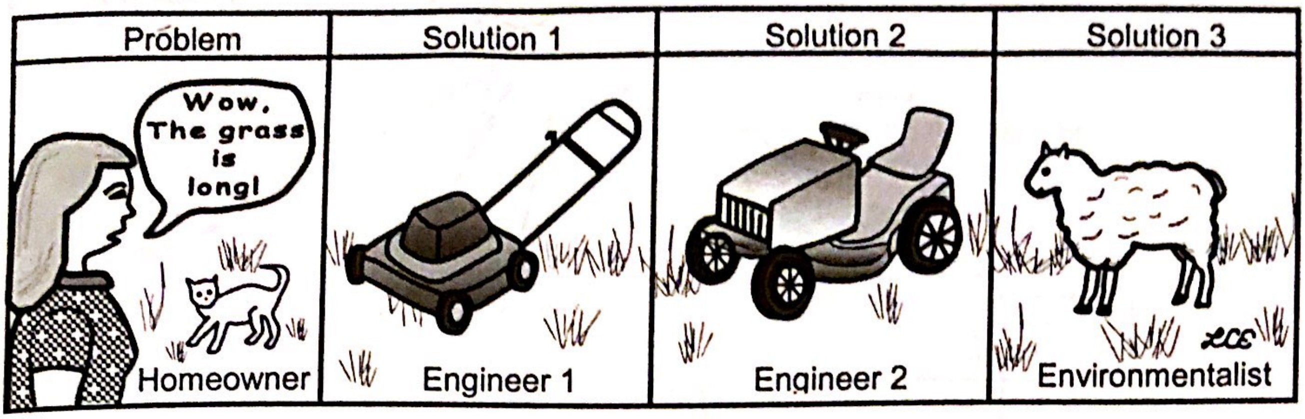
Tinkering as "Design." Throughout history we find examples of products that have not been engineered including: pots, pans, cutlery, chairs, sofas, and beds. Manufacturers of such "designs" employ new materials or try different fabrication methods without regard to the underlying sciences, and if successful, adopt them in their future products. As in artistic design, **tinkering** is not engineering design.

2.4 STRATEGIES FOR SOLVING DESIGN PROBLEMS

Is there an obvious strategy, or plan of action, for solving a particular design problem? Does the solution strategy depend upon the problem?

Let's reconsider the examples presented in Section 2.1.The *toaster* has a defect that needs to be remedied. The situation is annoying and potentially dangerous to the consumer. The toaster has a part or subassembly that is not functioning, causing the product to malfunction. If the company does not act promptly, it will likely suffer significant financial losses. The current *lawn mower engine* pollutes the air and will no longer be legally acceptable. This too is a problem that needs immediate solving, similar to the toaster problem. The *potato-chip-packaging equipment* works. It currently functions. However, it might be able to work better. It represents an opportunity that would likely lead to improved customer satisfaction and company profits. Similarly, the *light bulb, canoe paddle, car seat*, and *robot welder* are opportunities to improve performance, enter a new market, reduce costs, or serve a new customer. While problems need to be fixed, opportunities may be deferred. Design problems, therefore, exhibit varying amounts of urgency or necessity.

In addition to the urgency or necessity of solving a design problem, we might consider other factors. For example, we may not have enough time available to redesign a part or subassembly because the product's life cycle is too short. Or, we may not have enough manpower or other resources available in the company. We may have to settle for a quick fix. The technical challenges may be too risky. Or, it may be better to withdraw a poor product from the market than to poorly redesign a substitute. For example, a tire manufacturer might withdraw a specific brand of off-road tires because delaminating tread failures appear to result in rollovers of some sports utility vehicles. In this case, the company decided that the best *business* strategy was "not solve the problem."



Quite often, there are many alternative solutions to a design problem. Each of the three solutions will "cut" the grass. Solution 1 requires the user to walk behind the power lawn mower. Solution 2 permits the user to ride. Solution 3 requires no gasoline, walking or riding. But then again,... *other* waste products are generated.

A number of approaches or strategies can be used to solve a design problem. Let's reconsider the toaster design problem to illustrate some plausible strategies. Assume that we know that a defective part causes 5 percent of the manufactured toasters to fail during normal use. We might consider the following alternative strategies:

A. Change the part's thickness, length, or material

B. Reconfigure the part by rearranging some of its geometric features,

C. Select and purchase a similar part from a reputable supplier

D. Redesign the subassembly eliminating the defective part

E. Replace the part with one that uses a different working principle

F. Pursue combination of above

G. Discontinue the product, or

H. Do nothing.

We see that alternative A relates to revising a part's size. We can call this strategy choice a variant design or parametric design strategy. Alternative strategy B relates to changing a part's configuration, which we call configuration design. Choice C can be called a selection design strategy. Choice D can be called a redesign strategy. And similarly, choice E can be called a concept design strategy. We see that there are many viable technical approaches to solving the defective toaster part design problem. It may not be possible, given limited time and resources, to determine the root cause of the defect. Therefore, discontinuing the product may be the right business strategy.

We can also conclude that a design problem is different than the solution strategy. The toaster design problem was that it was defective. A defective part caused product failures. And moreover, we can use any one of a number of strategies to "solve" the problem.

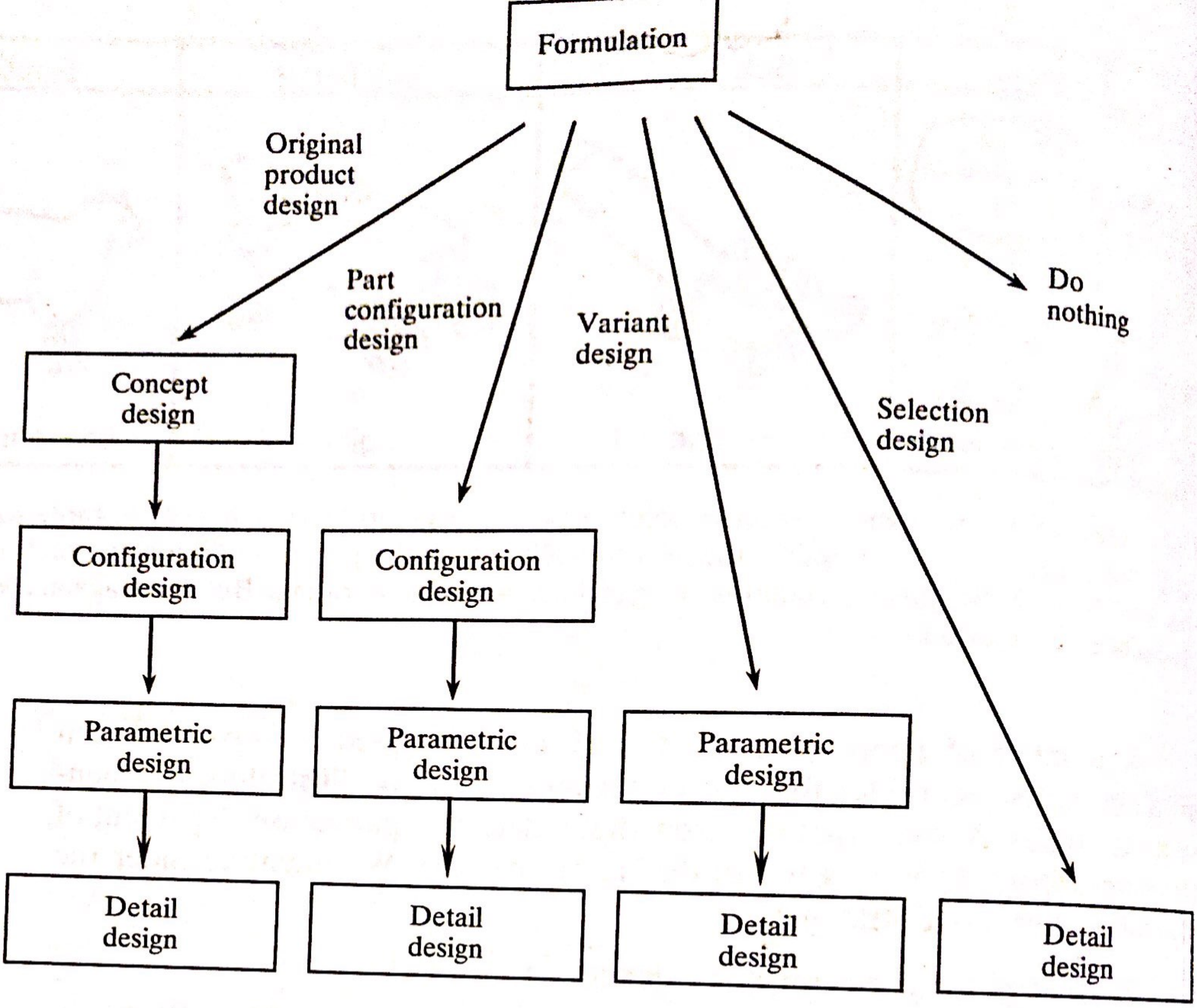


FIGURE 2.7 Formulation initiates all solution strategies.

Depending on the circumstances, a design problem may have a self-evident solution strategy. For example, if the toaster part was a standard part, and determined to be improperly fabricated, we would likely pursue alternative C: Select and purchase a similar part from a reputable supplier. Choosing an appropriate strategy is easier when we have more information, such as knowing the root of the problem, or the significance of the lost customer satisfaction. Unfortunately, we rarely have all the information! Therefore, self-evident strategies are rarely obvious, especially when we consider more complex components such as special-purpose subassemblies.

We cannot know for certain all the information that would lead to a perfect decision. It usually costs too much and takes too much time to gather. Businesses, however, make decisions on limited information all the time. Otherwise, the competition would pass them by.

One key to success in selecting the right, initial solution strategy is getting the right information. This is a major objective in design problem formulation. Figure 2.7 emphasizes that a given design problem may be solved in a variety of ways. But take particular note how formulation starts them all. We examine design problem formulation in the next chapter.

CHAPTER 3

Formulating a Design Problem

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Understand the complexities and subtleties of design problems
- Describe the overall process of formulating a design problem
- Determine customer and company requirements
- Describe and use sources of product and customer information
- Prepare engineering design specifications
- Understand and implement the House of Quality
- Establish a consensus among the team members and management

3.1 INTRODUCTION

Formulating a design problem is an exciting and challenging activity. Like a detective when solving a complicated homicide case, we investigate leads, uncover hidden facts, and determine motives. We pursue some dead-ends and have to backtrack. We may find our data to be false, or misleading, or uncertain. Conditions we once thought fixed may change during the investigation.

Often the initial description of a design problem lacks the type of information necessary for successful design and manufacturing. Whatever information there is may be too general, or incorrect, or not technically specific. As we begin we try to get an overall understanding of the situation. But then, as we become familiar with the problem, we probe deeper into various sources to obtain more details. Piece by piece, as the puzzle begins to take shape, we systematically and doggedly pursue the facts to build a solid foundation for solving the problem.

The process of formulating a design problem, as shown in Figure 3.1, usually includes four primary activities: seeking information, interpreting, gaining consensus, and obtaining management approval.

Seeking Information. We gather data from various information sources, including surveys and studies, to obtain a detailed understanding of the customer, his or her specific needs, and the competition.

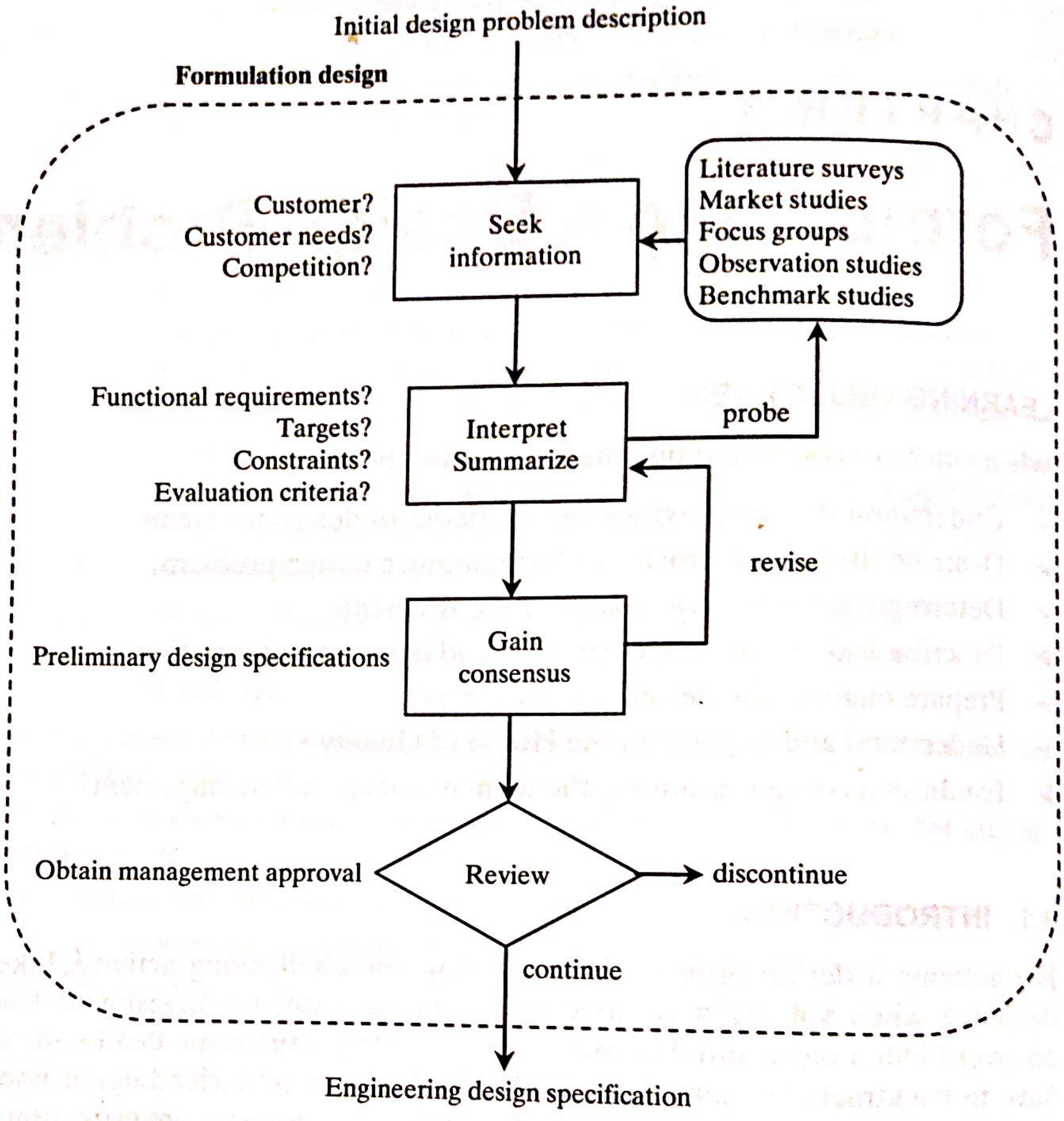


FIGURE 3.1 The process of formulating a design problem includes seeking and interpreting information, gaining team consensus on the basics of the problem, and obtaining approval from management to proceed.

Interpreting. As we translate the raw data, we detail the specific functional requirements of the part, assembly, or product, desired performance targets, necessary constraints, and evaluation criteria. If the data are too general or vague, we revisit information sources and probe deeper.

Gaining Consensus. The prior activities are diverging in nature and lead to an information explosion. To gain consensus, team members discuss their interpretations of the data, revising their conclusions and probe deeper into the data sources, if necessary, to resolve conflicts. Then they prepare a preliminary engineering design specification, which is a written "summary" of the problem.

Obtaining Management Approval. To keep management informed and to obtain their approval, the team presents the preliminary engineering design specification in a design review meeting, or in a memorandum or technical report.

The formulating process summarized in Figure 3.1 is no doubt an oversimplification of how individual teams formulate design problems in their companies. However, the figure does illustrate that a product development team processes a significant amount of information. The figure also emphasizes the need for a common understanding among team members and management.

In the next sections of this chapter we examine the specific types of information to be processed and methods that facilitate building consensus.

3.2 OBTAINING A DETAILED UNDERSTANDING OF THE DESIGN PROBLEM

The quantity and quality of information we obtain often depends upon whether the design problem pertains to a part, subassembly, or product. Imagine, for example, the original design of a high-performance motorcycle, versus the variant design of a multi cylinder internal-combustion-engine, versus the selection design of a ball bearing. Let's examine these specific situations to identify the types of information we might search for and acquire in any given design problem.

High-Performance Motorcycle Design Example. Motorcycle manufacturers such as Harley-Davidson, Honda, Kawasaki, and Suzuki design and manufacture millions of motorcycles each year, including off-road trail bikes, touring bikes, street bikes, and high-performance bikes. The high-performance bike is fast and maneuverable and consequently demands the utmost in engineering design skill. The team would normally seek information regarding:

- How quickly should the cycle accelerate to 60 miles per hour?
- What should the top speed be?
- How maneuverable should the motorcycle be?
- Is fuel consumption less important than acceleration?
- What riding comforts are expected?
- Is an electric starter desired?
- Will the customer tolerate a liquid cooling system?
- Will the customer care about aesthetics?
- Which is more preferred: low-end torque or high-end speed?
- What is the target cost of manufacture?
- What are the ambient air temperatures and humidity?

- What is the anticipated production run quantity?
- What types of instruments are preferred, digital or analog?

Multicylinder-Engine Design Example. Multicylinder internal combustion engines can be purchased by original equipment manufacturers (OEMs) for use in products such as: riding lawn mowers, auxiliary electric power generators, and powerboats. While most engine manufacturers have standard lines of 2-, 4-, 6-, or 8-cylinder engines, they will custom-design engines for special OEMs. To complete a custom design, however, the team would consider requirements such as:

- What fuel will the engine burn?
- What horsepower and torque are required at what speeds?
- Are there any height, width, and or depth size constraints?
- Is there a preferred output shaft size?
- Will the engine run at full speed all the time?
- What features or performance issues are important?
- Will the engine run at idle speed for long periods?
- Is an electric starter preferred?
- What will the ambient air temperatures and humidity be?
- How long should the oil and air filters last before replacement?
- Will an integral fuel tank be required?
- What is the desired life expectancy in operating hours?
- What is the desired service interval for valve clearance and timing?
- What safety standards will apply?
- Will components be made in-house or purchased?
- What is the desired specific fuel consumption (gal/hr per hp)?
- What new factory tooling will be required?
- What is the target cost of manufacture?
- What is the anticipated production run quantity?

Ball-Bearing Selection Design Example. Ball bearings are standard subassemblies made by a number of manufacturers. Each subassembly includes: an outer ring, inner ring, balls, and ball separator. Optional features include shields and seals. When we design a ball bearing we select a type and size from a manufacturer's catalog based on rated load capacity. The type and size depend on a number of requirements, including:

- Will the bearing be subjected to impact?
- What radial and thrust loads will the bearing need to support?
- What will the operating speed of the rotating ring be?
- Will the bearing need to be self-aligning?

- Will the bearing need to be shielded from dirt and dust?
- Will the bearing need to be sealed against liquids?
- How will the bearing be lubricated?
- How many rotations should 90 percent of the bearings survive at the rated loads?
- How will the bearing be mounted?
- What will the range of air temperatures and humidity be?
- How many units will be purchased?
- What type of warranty does the supplier provide?

As we see from these examples, during formulation we actively search for, acquire, and interpret essential details of the design problem involving: what product functions are desired, how well the functions are performed, the operating environment that the product is subjected to, as well as marketing, manufacturing, and finance concerns. These can be broadly classified into **customer requirements** and **company requirements.**

3.2.1 Customer Requirements

Fundamentally, products are bought to satisfy needs and wants. Products have value. They provide utility to the customer. Value can be defined as the ratio of benefits to costs. The greater a product's benefits, in relation to its costs, the more the value it has and, usually, the greater the customers' satisfaction. If we listen carefully to the "voice of the customer," and endeavor to identify important customer requirements, we will most likely maximize our customers' satisfaction.

Function and Performance. The most important requirement of a product is that it should work. In other words, it should perform one or more functions. The principal function of a motorcycle, for example, is to transport a person. However, if we decompose, or subdivide, the main function into subfunctions we might understand our customer a little better. For example, a motorcycle performs a number of subfunctions, including: transport rider(s) fast, steer bike easily, support rider(s) comfortably, absorb road shocks, and start engine quickly. Products or parts produce or react to forces and moments. They also provide motion (kinematics), convert types of energy, or control matter or energy. For example a:

- screwdriver drives a screw by pushing and twisting,
- coffeemaker converts electricity to heat water for brewing,
- wall switch connects house current to control overhead light,
- pencil transmits hand force to graphite tip to mark paper,
- ship propeller converts rotational shaft torque to thrust force,

- hammer drives a nail with an impact force, and
- thermostat senses temperatures to control furnace and blower.

Note how the functions performed by the product generally relate to energy, matter, and signal (i.e., control). We will discuss these and other functions and subfunctions in more detail in Chapter 4, "Concept Design."

After we determine the primary functions that our customer desires, we try to ascertain how important each function is to the customer. For example, the customer often describes more important functions as those that *must* be included versus those that *should* be included. Pahl and Beitz (1996) describe a "must" function as a demand and a "should" function as a want. Both sets of descriptors are in common use. In addition to using words as importance descriptors, design teams sometimes estimate importance using quantitative **importance weights**, as shown in Table 3.1. Note that the total adds up to one, or 100 percent. As we will see in later chapters, importance weights are measures that can be used to evaluate alternatives. An alternative to importance weights is the use of importance ratings, or measures that use ordinal numbers scales, such as "5" for most important, "3" for important, and "1" for not important. Not everything is important. We must determine the importance of each function.

TABLE 3.1 Customer Importance Weights By Function.

Function		Weight
transport rider(s) fast		50 %
steer bike easily		20 %
support rider(s) comfortably		10 %
absorb road shocks		5 %
start engine quickly		15 %
	total	100 %

Operating Environment. The operating environment for a product includes maximum and minimum air temperatures, humidity, and pressure. A motorcycle operating in a desert climate, for example, will experience extremely high air temperatures and low humidity, as compared to cooler mountain climates with lower air pressures at higher elevations. We might also consider dirt, mud, dust, corrosive gases (e.g., chemical vapors/pollutants) or liquids (e.g., salt spray), shock, and vibration.

Safety. Products must not injure anyone or damage anything during their installation, use, or retirement. Manufacturers are ethically and legally responsible to ensure that their products are free from hazards caused by defects of design and manufacture.

Economic. Customers may have specific economic requirements, including: the initial price they pay, installation fees, delivery charges, financing ex-

penses, repair and maintenance expenses (e.g., replacement parts, lubricants), useful life before replacement, salvage value (e.g., resale or trade-in value), and disposal costs. Taken as a whole, these are often called the life-cycle cost of ownership. Customers typically scrutinize the life-cycle costs of expensive consumer products such as appliances and vehicles. Government and business customers "justify" company purchases using life-cycle cost/benefit analyses.

Geometric Limitations. The product may need to fit in a space limited by height, width, and or depth. Or it may need to be connected at certain locations or have some angular requirements. Note that this category should not be used to set specific sizes or configurations of a product. It should rather consider only limitations on overall sizes or configurations.

Maintenance. Maintenance requirements include how and when the product is cleaned, adjusted, and/or lubricated for proper working condition. The need for special training and/or tools to perform the maintenance should also be considered.

Repair. The costs and convenience associated with broken or worn parts may be of importance, especially for unexpected breakdowns or damage due to accidents.

Retirement. A product may need to be disassembled at the end of its useful life for remanufacturing or recycling some of its components. Some components may have scrap value. Others may have disposal fees and require regulatory procedures.

Reliability. Customers expect their products to work all of the time. Reliability is a measure of the likelihood that a product and all of its components work.

Robustness. A robust product performs in spite of variations in its material properties, how it was manufactured, the operating environment, or how it is used. For example, customers might be somewhat dissatisfied when a product's moving parts jam because of thermal expansion.

Pollution. The customer may require specific considerations of air, water, and noise pollution.

Ease of Use. Will the product require special controls to operate effectively (e.g., air-conditioner thermostat, automatic garage door opener)? Will the customer need to be trained before using the product (e.g., private airplane, all-terrain vehicle, computer numerical control (CNC) machine, or firearm)? In other words, will the product be user-friendly?

Human Factors. When a product is used, controlled, or operated by a person, human factors must be considered, such as the user's ability to apply forces and torques, body size and range of motion (i.e., hands, feet, arms, and legs), and ability to sense (i.e., touch, hear, or see).

Appearance. Does the customer have any specific requirements as to color, shape, surface finish, texture, and/or aesthetics?

3.2.2 Company Requirements

Successful products must also satisfy company requirements as well as customer requirements. As mentioned in Chapter 1, the company will make a significant investment during the product development phase and the manufacturing ramp-up, before the product provides any sales revenues. Considering that it may take months, if not years, of continuous sales revenues to pay for these early investments, the company will have requirements pertaining to marketing, manufacturing, and financing.

Marketing Marketing requirements involve specifying product features, options, prices, warranties and delivery times. The marketing group will also investigate the competition and what it will be doing during the time it takes to get the product on the market (i.e. "time to market"). The company may decide to pursue a strategy to serve a specific segment of the market, such as large discount chains, or develop a product for a "high-end" niche market. The company will also try to estimate the necessary advertising resources and the annual volume that should be produced and sold.

Knowing whether the customer is an individual, group, business, or government agency can make a big difference. Some products are bought by two or more people, such as an automobile or family home appliance. In such cases the evaluation of individual products and the decision to purchase is made by two or more people. Similarly, businesses buy products such as photocopy machines, milling machines, personal computers, and welding robots. However, businesses often establish rigorous criteria and purchasing procedures that involve significant rational decision making. Similarly, government agencies buy products, such as helicopters and tanks. Obtaining an understanding of the federal agency's evaluation criteria and procedures is instrumental for the company's success.

Lastly, **customers** purchase products. **Consumers** use them. Grandparents, for example, are customers who buy toys for their grandchildren consumers. As toy designers we would want to examine whether the customer might consider safety over and above entertainment value.

Manufacturing Manufacturing requirements pertain to purchasing, fabrication, assembly, warehousing, and distribution. Since the final cost of a product relates to labor, materials, and manufacturing processes used, each company may have special advantages or limitations to take into consideration.

Perhaps the most important factor is the expected annual production volume (number of units made). Mass-produced food products, chemicals, automobiles, light bulbs, and refrigerators use continuous production processes. Raw materials, parts, and subassemblies flow through the factory plant without being stored. Batch production, which fabricates and inventories parts and subassemblies in batches, is often used to make products such as bicycles, helicopters, inflatable kayaks, and milling machines. A custom-design machine tool is an example of "one-off" production. High-production-volume manufacturing processes such as injection molding

and die casting would not be considered for it. Lean manufacturing is a production practice that tries to minimize inventory handling and storage often associated with batch production.

Financing The product development team will also obtain information that can be used to prepare estimates of the capital expenditures necessary to purchase and install manufacturing equipment or modify existing facilities. Similarly, projections of sales revenues, expenses, profits, and return on investment will be estimated. These estimates are usually prepared and updated throughout the product development project. The figures are periodically reviewed by senior management to determine whether to continue or terminate the project.

Other In some cases, existing patents may block the product design. If a license agreement cannot be negotiated with the patent holder, a new design concept will have to be considered. Similarly, legal and voluntary regulations, standards, and codes need to be examined.

A summary of fundamental customer and company requirements is presented in Table 3.2.

3.2.3 Engineering Characteristics

Next we select **engineering characteristics**, or measures that can quantify how well a product performs each requirement. For example, what does a motorcycle customer mean when she says that she wants to go fast? We might consider

TABLE 3.2 Fundamental Customer and Company Requirements

Customer Requirements	Company requirements
Functional performance	Marketing
Motions/Kinematics	Customer / Consumer
Forces/torques	Competition
Energy conversion/usage	Strategy
Control	Time to market
Geometric limitations	Pricing
Operating Environment	Advertising
Air temp., humidity, pressure	Sales demand / targets
Contaminants	Manufacturing
Shock, vibration	Production quantity
Human Factors	Processes, Materials
Economic	New factory equipment
Safety	Warehousing & distribution
Appearance	Financial
Reliability	Product Development Investment
Robustness	Return on investment
Maintenance	Other
Pollution	Regulations, Standards, Codes
Repair	Patents / intellectual property
Retirement	

quantifying the "go fast" requirement by selecting top speed measured in miles per hour, or maximum acceleration measured in feet per second per second, or both. Similarly, we might quantify "start quickly" by selecting cranking time measured in seconds.

Engineering characteristics are essential to the design process. They should be objective and not subject to interpretation. First, they can be can be used to impartially assess how well an *existing product* satisfies its customer requirements. Second, since engineers use these same measures in formulas to predict the physical behavior of objects, we can use engineering characteristics to assess how well a *new product* might perform. The phrase "engineering requirements" is sometimes used in industry to describe these measures. Requirements, however, are somewhat different from characteristics. A "requirement" is more of a desirable or necessary target value for an engineering characteristic. A "characteristic" is really the means to establish a "requirement." Therefore, in this text we refer to these quantitative measures as engineering characteristics.

We also designate appropriate units and limits for each engineering characteristic. Limits refer to minimum or maximum values that customers often demand, such as: needing *at least* 10 miles per gallon of fuel. A few engineering characteristics for the motorcycle example are given in Table 3.3.

TABLE 3.3 Engineering Characteristics, Units and Limits.

Subfunction	Engineering Characteristic	Units	Limits
start engine quickly	cranking time	seconds	≤ 6 sec
support rider(s) comfortably	cushion compression	inches	
transport rider(s) fast	acceleration	feet/sec^2	≥ 32 ft/s^2
	top speed	mph/kph	≥ 90 mph
	0-60 mph	seconds	≤ 6 sec
steer bike easy	steering torque	pound-ft	
	turning radius	feet	
absorb road shocks	suspension travel	Inches	> 5 inches

3.2.4 Constraints

Restrictions on function or form are called **constraints**. Constraints limit our freedom to design. Maximum or minimum performance limits relating to the desired functions or subfunctions are appropriately called constraints. Specific limitations regarding shape, size, configuration, materials, or manufacturing processes are also called constraints. Constraints also originate from economic or legal considerations. Finally, constraints derive from the laws of nature. The conservation of energy, and static equilibrium for example, are often used to develop constraints.

During formulation, we take careful note of all explicitly stated constraints. For example, "injection molding must be used," "the customer requires aluminum components," "a round tank is required." "The length

must be less than 5 feet," or "a left-handed thread is required." Implicit constraints, on the other hand, are those restrictions that are implied, or generally understood, but not directly stated. For example, the customer implicitly wants a safe product. More generally, safety implies that all the parts will not buckle, fracture, melt, corrode and so on.

We must consider implicit and explicit design constraints.

When a design for a part, product or process satisfies all the constraints it is called a feasible design. Those alternative designs violating any constraints are said to be infeasible. During the parametric design phase we will generate a number of alternative designs, predict their performance, and check that the constraints are satisfied for each design. Only those designs that are feasible will be developed further.

3.2.5 Customer Satisfaction

Finally, contemporary product design teams try to qualify or quantify how satisfied a customer is at various levels of performance. Satisfaction is a measure of the utility a product provides (Badiru and Pulat, 1995; Dixon and Poli, 1995; Hazelrigg, 1996; Keeney and Raiffa, 1976; Siddall, 1982; Stub et al., 1994). In other words, design teams try to estimate customer satisfaction with respect to key engineering characteristics. For example, would a top speed of 90 miles per hour be unsatisfactory, moderately satisfactory, or highly satisfactory for a high-performance motorcycle? How much more satisfaction is there at 120 or 150 miles per hour?

Customer satisfaction is extremely important. First, we need the customer to tell us what a good or excellent design is. We should not impose our values of good or bad. A high-performance motorcycle customer might value a 90-miles-per-hour top speed bike as unsatisfactory, even though we might value it as good or excellent. Second, we should try to establish qualitative or quantitative levels of satisfaction. We could then measure how good an existing product is, or how good a competitive product is or a new design might be.

What performance would the customer consider as unsatisfactory, poor, fair, good, or excellent? Continuing with the motorcycle example, we might find that various top speeds would result in the qualitative levels of satisfaction shown in Table 3.4. Note that the table uses qualitative words such as not satisfied, somewhat satisfied, and moderately satisfied.

A quantitative means to express customer satisfaction is to use numerical values. For example, when the customer is not satisfied, we quantify it with the number 0 (i.e., 0 percent satisfied). When the customer is most satisfied, we quantify his/her satisfaction value as 1 (i.e., 100 percent satisfied). Similarly, other values can be established for levels in between, as shown in Table 3.5. Although somewhat subjective, quantitative satisfaction values can be used to evaluate the "goodness" of existing products or new design candidates.

TABLE 3.4 Qualitative Satisfaction Levels Based on Top Speed

Top-speed (mph)	Satisfaction level
0 < speed ≤ 90	Not satisfied
90 < speed ≤ 100	Hardly satisfied
100 < speed ≤ 110	Somewhat satisfied
110 < speed ≤ 120	Moderately satisfied
120 < speed ≤ 135	Very satisfied
135 < speed ≤ 150	Most satisfied
speed > 150	Most satisfied

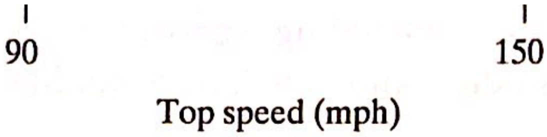
TABLE 3.5 Quantitative Satisfaction Values Based On Based on Top Speed

Top-speed (mph)	Satisfaction level	Value
0 < speed ≤ 90	Not satisfied	0.0
90 < speed ≤ 100	Hardly satisfied	0.3
100 < speed ≤ 110	Somewhat satisfied	0.5
110 < speed ≤ 120	Moderately satisfied	0.8
120 < speed ≤ 135	Very satisfied	0.9
135 < speed ≤ 150	Most satisfied	1.0
speed > 150	Most satisfied	1.0

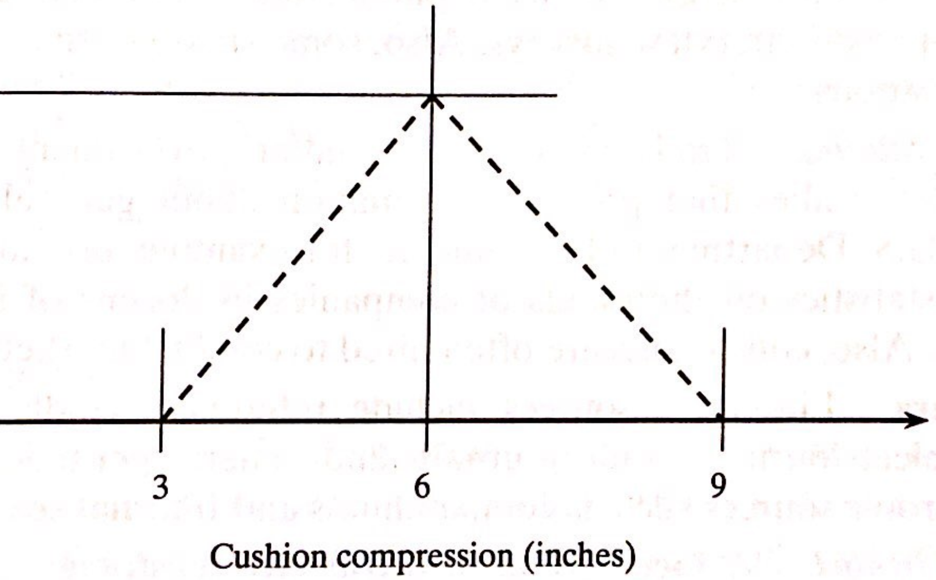
Graphing provides a third means to provide satisfaction values as a function of a performance variable. Let's continue with the high-performance motorcycle. Using focus groups and other customer satisfaction assessment information, we might decide that our customers would be totally unsatisfied with a bike having a top speed of less than 90 miles-per-hour. Further, we decide that the customer would be totally satisfied with any speed greater than 150 miles per hour. Let's also assume that the customers would be proportionately satisfied in between those speeds. Let's use the value of 0.0 for not satisfied and 1.0 for totally satisfied. Rather than using a table, we graph a *satisfaction versus "top speed"* curve as the dashed line shown in Figure 3.2. We could similarly decide the customer's satisfaction with respect to cushion compression and cranking time, as shown in Figure 3.3 and Figure 3.4.

Using the **customer satisfaction curves** for cushion compression and cranking time, we can readily determine that the customer will be unsatisfied with cushions too soft or too stiff, and that a cranking time greater than 6 seconds is unacceptable. Having that knowledge, in a quantifiable manner, will help us decide which motorcycle design candidates are "better," that is, satisfy our customer the most.

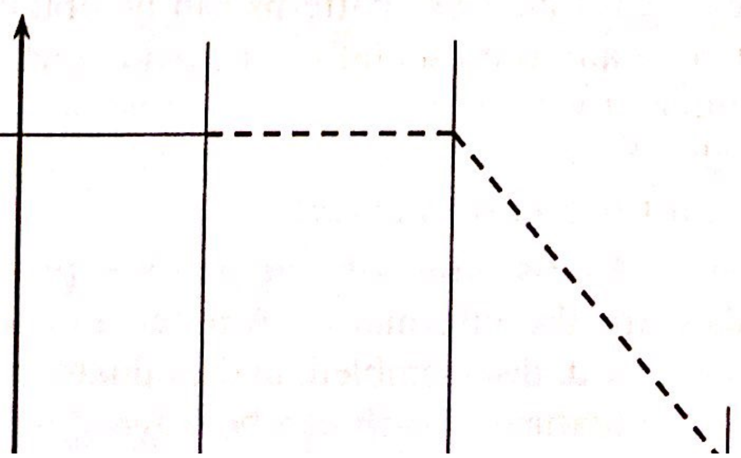
In general, satisfaction curves fall into three categories: 1) more-is-better, (2) target-value-is-better (i.e., nominal-is-better), and (3) less-is-better. These same categories are illustrated in Figures 3.2–3.4. Note that the shape of a satisfaction curve is arbitrary and may be curved rather than linear. The curves are shown here as dashed lines to emphasize that they are estimates of the



tion as a function of top speed (mph). This is an example of a
onship (i.e., more top speed results in more customer satisfaction).



ion versus cushion compression (in.). This is an example of a "target is
greatest customer satisfaction occurs at target value).



customer's satisfaction. More examples will be discussed later in Chapter 8, Parametric Design.

Most important, we recognize that even though the shape of the curve is arbitrary and the end points are only estimates, we should try to understand how our customer appreciates different levels of performance. Our thorough understanding will help us make better design decisions.

3.3 INFORMATION SOURCES

As we formulate our design problem we search for and examine information from a variety of sources, including: surveys, market studies, literature, focus groups, observation studies, and benchmark studies.

Surveys. Perhaps the first place to look is inside the company. Many companies have established customer feedback systems that include: service reports, customer support reports, and warranty claims. Customer surveys provide a major source of information on existing and potential customers. Customers can be queried using phone, mail, and e-mail surveys in addition to in-person interview surveys. Also, some surveys are available from trade associations.

Market Studies. Trade associations, and/or government agencies, publish market studies that provide information about general customer trends. The U.S. Department of Commerce, for example, provides annual production statistics on thousands of companies in dozens of industry classifications. Also, consultants are often hired to conduct market studies .

Literature. Literature sources include reference handbooks, monographs, technical journals, trade journals, and general periodicals, in addition to electronic sources such as compendiums and Internet searches.

Focus Groups. A **focus group** of prospective customers can be gathered in one location to discuss a new product (Crawford and DiBenedetto, 2003). The participants are usually compensated for their time and a highly trained moderator often leads the discussion.

Observation Studies. Customer use patterns can be obtained by observation studies wherein company representatives or paid consultants observe customers as they interact with a product, without being seen themselves. For example, we might observe a shopping mall parking lot, to investigate how people use their car trunk to stow parcels.

Benchmark Studies. Assessments of competitive products, often called **benchmark studies**, are also informative. A number of competitive products are identified, purchased, disassembled, and evaluated with respect to their common and unique features. Much can be learned about how each product attempts to satisfy customer and company requirements.

How much information is enough? Which sources of information are more reliable? The answers depend on the time and money available to the team, and the consequences of false, misleading, or insufficient information.

To help us answer these difficult questions, we should consult company experts and upper management for their experience, wisdom, and guidance.

Note that the information gathered involves many departments from across the company. It is no wonder, therefore, that successful product design teams have representatives from sales and marketing, engineering, finance, and manufacturing. In addition, recall that the industrial designer on the team will focus on desired aesthetics, while the design engineer will concentrate on the desired functions.

In the next section we examine Quality Function Deployment (QFD) and the House of Quality for product planning. The house of quality, in particular, is an outstanding method that systematically structures and develops the design problem information.

3.4 QUALITY FUNCTION DEPLOYMENT/HOUSE OF QUALITY

As we consider the entire product realization process, from identifying customer requirements to delivering the finished product, we recognize that thousands of decisions by many different people using various evaluation criteria are involved. Hopefully our company will appoint a concurrent engineering product development team that is collocated, cross functional, and coordinated by a high-ranking manager. But will the product have the quality that the customer is expecting?

3.4.1 What Is Quality?

Consumers were surveyed by *Time* magazine (1989) about what a **quality product** is? The most frequent responses were: (1) works as it should, (2) lasts a long time, and (3) is easy to maintain. An earlier work by Garvin (1987) corroborates the survey's findings by identifying the following characteristics of quality: (1) performance, (2) features, (3) reliability, (4) durability, (5) serviceability, (6) conformance to conventions/standards, (7) aesthetics, and (8) perceived quality/ reputation of manufacturer.

Since a product is as good as its parts, a quality *product* is made of quality *parts*, which are made by high-quality manufacturing processes. Consequently it will function or perform as expected (reliable), last a long time (durable), and be easy to maintain (serviceable), among other things. But, which department in the company is responsible for quality? Is it sales and marketing? Production? Engineering design? Other?

3.4.2 Quality Function Deployment (QFD)

Every department contributes to the quality of the product, and is therefore responsible. Just like the responsibility for financial matters is a business function that can be assigned to a group of employees in the "finance"

department, so can quality. But everyone in the company is responsible for quality. How can we assign or "deploy" quality throughout our company? We can't call every department the quality department. Yes, there is the quality control "department." But that group is usually responsible for only a limited set of raw material and finished goods tolerance checking activities. But, don't we need to have all the departments focus on quality?

Quality Function Deployment (QFD) is a team-based method that draws upon the expertise of the group members to carefully integrate the voice of the customer in all activities of the company. The method makes use of discussion groups to systematically address product, part, process, and production quality. Group discussions are summarized in four houses of quality diagrams that structure (1) product, (2) part, (3) process, and (4) production information. Since representatives from all corners of the company are involved in the decision making, the method achieves a high level of consensus, and consequently results in high-quality products. In other words, quality, as defined by the customer, is deployed throughout the company. Let's examine the first of the four houses, the house of quality for product planning.

3.4.3 House of Quality for Product Planning

The "**House of Quality**" **(HoQ)** for product planning is a systematic graphic representation of product design information organized as a matrix of "rooms," "roof," and "basement."The house of quality is a useful and illustrative summary of product information. The three other houses of quality (part design, process planning, production planning) will be discussed later in this chapter.

The real value of the HoQ is not the diagram. Rather, the real value lies in the required group discussion and decision making, which leads the team to a common understanding of the design problem.

Recall that during problem formulation the team tries to obtain a detailed understanding of the design problem. It gathers and evaluates information relating to: customer and company requirements, their importance weights, engineering characteristics, and competitive products used as benchmarks. Some of this work will be done in groups. But, a lot of the work will be done individually. If discussion and summary are a group activity, however, the team is likely to obtain a consensus of opinion on many aspects of the product design requirements.

The HoQ for product planning, shown in Figure 3.5, systematically structures the following information: 1. customer requirements, 2. customer importance weights, 3. engineering characteristics, 4. correlation ratings of requirements and characteristics, 5. benchmark satisfaction ratings, 6. benchmark performance values, 7. new product design target values and 8. coupling between engineering characteristics.

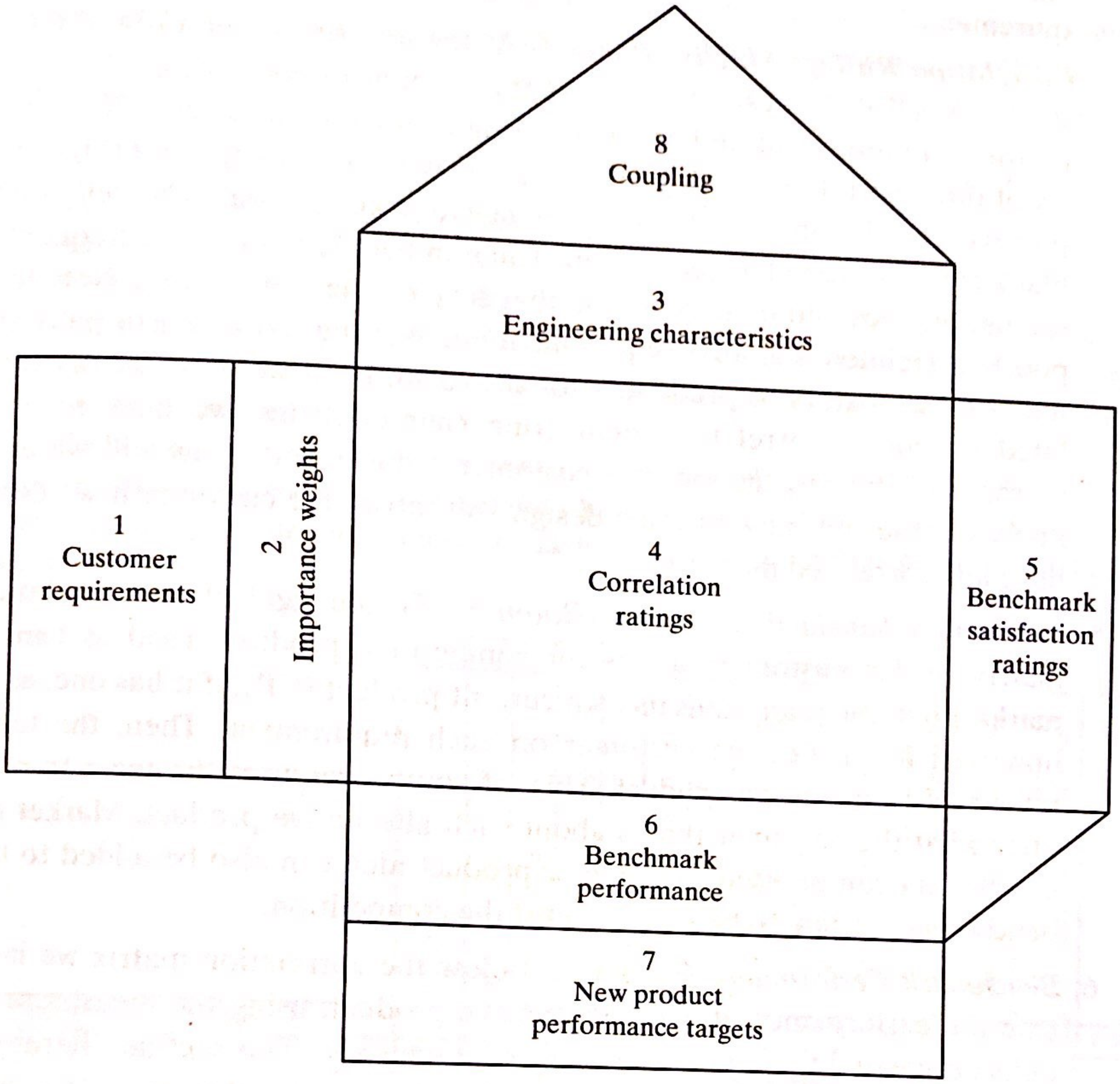


FIGURE 3.5 Rooms of the product planning House of Quality structures important information.

1. *Customer Requirements (Room 1).* Customer requirements are summarized as rows in the first column. A clear list of functions and subfunctions focuses on important needs of the customer. Customer wording or terminology is frequently used to express the "voice of the customer." The list should contain only the more important requirements and rarely exceeds 25 items.
2. *Customer Importance Weights (Room 2).* Adjacent to the requirements column is the importance weights column. Using values between 0.0 and 1.0, the weights establish how important the customer considers each requirement with respect to the other requirements. The importance weights sum to 1.0.
3. *Engineering Characteristics (Room 3).* Along the top row, underneath the roof triangle, is a list of quantitative performance parameters and their

associated units, arranged in a row vector. An engineering characteristic can be used to quantify the amount of satisfaction of each customer requirement.

4. ***Correlation Ratings Matrix (Room 4).*** At the intersection of a row and column is a cell that is used to indicate the amount of correlation between a customer requirement and an engineering characteristic. Each cell is given six of three correlation rating numbers: 1 (low), 3 (medium), or 9 (high) for positive correlation and -1, -3, -9 for negative correlation. The cell is left blank for no discernible correlation. The numbers 1, 3, and 9 are frequently used in practice, although other number schemes have been used. Note that poorly correlated customer requirement/engineering characteristic pairs are not good indicators or predictors for the team. If all we have are uncorrelated or poorly correlated engineering characteristics, we have no real measure of the satisfaction of a customer requirement. How will we ever know whether our new product design will satisfy the customer if we don't have any correlated measures?
5. *Benchmark Satisfaction Ratings (Room 5).* To the right of the correlation matrix we list customer ratings for competitive products used as **benchmarks**. First, the team rates its own current product (CP), if it has one, as to how well it satisfies the customer on each requirement. Then, the team rates each competitive product. This, of course, requires the team to consider what the customer thinks about each alternative product. Market research data can be used too. A new product idea can also be added to the benchmark section, to be rated against the competition.
6. *Benchmark Performance* (Room 6). Below the correlation matrix we indicate the performance of each benchmark product, using the measurement units designated for each engineering characteristic. This section, therefore, is an arrangement of statistics gathered on the competitive products as to how well each product performs or "measures up."
7. *New Product Targets* (Room 7). Below the performance statistics, in the basement, we list **performance targets**, or desirable goals for the new product.
8. *Coupling Matrix* (Room 8). The triangular roof of the HoQ, called the **coupling matrix**, is a matrix of values that estimate the amount of coupling, or interaction, between engineering characteristics. Rating numbers such as 1 (low), 3, and 9 (high) are given for positive coupling and -1, -3, and -9 for negative coupling. Uncoupled engineering characteristics can be optimized, one by one, without affecting other engineering characteristics. Inversely correlated characteristics indicate that compromises will need to be made, or "trade off." In other words, if we improve one characteristic we will worsen the other.

Example

A product development team has been formed to design a new electric pencil sharpener for use in homes or offices. The team has obtained market research data and, combined with their own surveys, have come to a consensus about the major customer requirements including: doesn't slide when using, needs little insertion force, requires little insertion torque, operates when pencil is inserted, collects pencils shavings well, empties shavings easily, plugs into wall socket easily, cord is long enough, grinds pencil to sharp point, and needs only one hand two operate. Through a process of voting they also determined approximate importance weights for each.

After considerable discussion they agree upon the following engineering characteristics: slides (yes/no); friction factor, start switch force (lbf.), insertion force to sharpen (lbf.), hold force required (lbf.), grasp torque (in.-lbf.), shavings storage volume (cu. in.), number of steps to empty, standard 120 VAC (yes/no), cord length (ft.), point cone angle (degrees), number of hands to operate, weight (oz.), and point roughness (micro in.).

Then, systematically, they discussed correlation ratings, customer satisfaction ratings, and coupling ratings and establish new product targets. They summarized their understanding of the product design problem in a house of quality for product planning, shown in Figure 3.6a and Figure 3.6b.

			Engineering Characteristics (units)														Customer Satisfaction Rating (0.00 - 1.00)		
		Importance wt.	slides (yes/no)	friction factor	start switch force (lbf)	force to sharpen (lbf)	hold force required (lbf)	grasp torque (in-lbf)	shavings storeage (cu.in.)	no. steps to empty	120 VAC (yes/no)	cord length (ft)	point cone angle (degrees)	no. hands to operate	weight (oz)	point roughness (micro in.)			
Customer Requirements			1	2	3	4	5	6	7	8	9	10	11	12	13	14	CP	A	B
1	doesn't slide when using	0.10	9	3	3	3	9	1						3	3			0.9	
2	needs little insertion force	0.05			9	9												0.8	
3	requires little insertion torque	0.05						9										0.9	
4	operates when pencil is inserted	0.15			9									9				1.0	
5	collects pencils shavings well	0.05							9	1								1.0	
6	empties shavings easily	0.20							3	9		1		3	-3			0.6	
7	plugs into wall socket easily	0.05									9							0.9	
8	cord is long enough	0.05										9						0.8	
9	grinds pencil to sharp point	0.20											9			3		0.7	
10	needs one hand two operate	0.10		3										9	3			0.8	
	Total Importance	1.00																	

Interaction Matrix

Engineering Requirements	Engineering Requirement	1 slides (yes/no)	2 friction factor	3 start switch force (lbf)	4 force to sharpen (lbf)	5 hold force required (lbf)	6 grasp torque (in-lbf)	7 shavings storeage (cu.in.)	8 no. steps to empty	9 120 VAC (yes/no)	10 cord length (ft)	11 point cone angle (degrees)	12 no. hands to operate	13 weight (oz)	14 point roughness (*micro in.*)
slides (yes/no)	1		3	9	9	-3								-9	
friction factor	2														
start switch force (lbf)	3				1										
force to sharpen (lbf)	4					9	1								
hold force required (lbf)	5													-9	
grasp torque (in-lbf)	6												1		
shavings storeage (cu.in.)	7								3					3	
no. steps to empty	8												1	-3	
120 VAC (yes/no)	9										1				
cord length (ft)	10													1	
point cone angle (degrees)	11														
no. hands to operate	12													-3	
weight (oz)	13														
point roughness (micro in.)	14														

GURE 3.6b The "roof" of the House of Quality for an electric pencil sharpener is shown here in a convenient spreadsheet format.

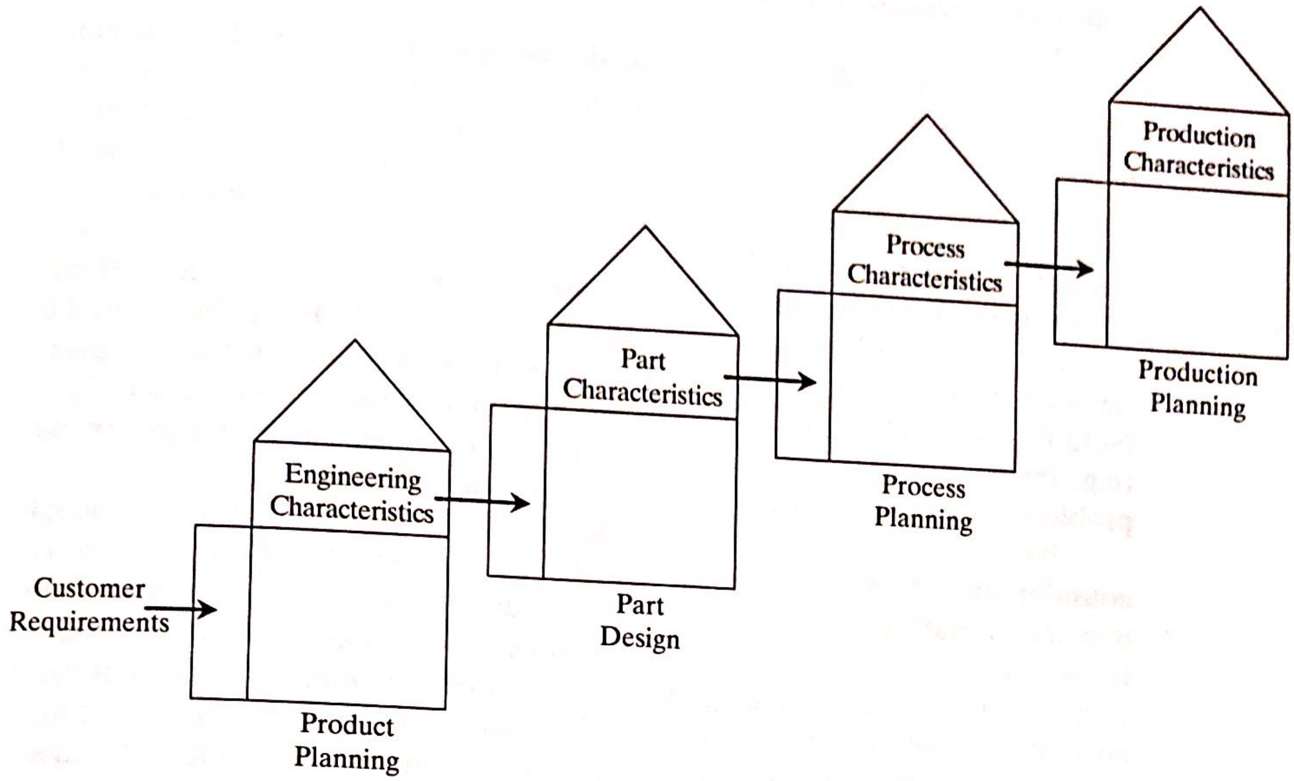


FIGURE 3.7 Quality function deployment method uses cascading house of quality diagrams to structure product, part, process, and production information

Further information on quality function deployment and the house(s) of quality can be found in Clausing (1994); Cohen (1995); Hauser and Clausing (1988); King (1989); Summers (1997); and Urban (1993).

3.5 PREPARING AN ENGINEERING DESIGN SPECIFICATION (EDS)

In the early phases of the formulating process, we gather, examine, and evaluate information regarding customer requirements, company requirements, engineering characteristics, constraints, and customer satisfaction.

At this juncture, we usually devote some effort to summarizing the design requirements in a document commonly called an **engineering design specification**, or EDS. The information is fresh in our memories and we need to consolidate the notes of our individual team members. More important, some members may have different interpretations of the data, which need to be resolved. This may be especially true if we did not prepare a house of quality for product planning. Therefore, discussing and documenting the engineering design specification is more than recording the team's findings. It is a useful process that can correct misunderstandings and clarify terminology

among team members from other departments. It is a homogenizing process that usually results in a common understanding of the customer's needs and priorities.

Consequently, the engineering design specification (EDS) is a single document that captures the whole team's understanding of the *specific details* of the design problem (Dieter, 2000; Dixon and Poli, 1995; Haik, 2003). It includes information on customer requirements, company requirements, engineering characteristics, constraints, and customer satisfaction. An example template, which lists some of the more important categories, is shown in Table 3.6. In some cases it is only one page long and in others it may be dozens of pages long. Of course, the contents of an EDS will be tailored to the item being designed, i.e., part, subassembly, product, system, or plant. Note that the EDS is sometimes called a product design specification (PDS) (e.g. Pugh, 1991). This step is equivalent to preparing a "statement of the problem" that we find in general problem-solving methods.

Not all of the details will be known at this time. Therefore, we should consider the engineering design specification to be a work-in-progress and dynamic in nature. As we develop the product, more information and knowledge develops. Therefore, we can fine-tune the EDS as we proceed, even up to the point of production engineering. Of course, the more we can set forth in an EDS, the better. That will save us time and effort since in a manufacturing enterprise, changes are documented by engineering change notices that need to be circulated through the company for approval signatures.

TABLE 3.6 Engineering Design Specification template

Cover page
- Title, date, stakeholders

Introduction
- Design problem description
- Intended / unintended uses
- Special features

Customer Requirements
- Functional performance
- Operating Environment
- Human Factors
- Economic
- Safety
- Appearance
- Reliability
- Robustness
- Maintenance
- Pollution
- Repair
- Retirement

Company requirements
- Marketing
- Manufacturing
- Financial
- Regulations, Standards, Codes
- Patents / intellectual property
- Other

Appendices
- Site visit data
- Sales/Marketing data
- House of Quality

Engineering design specification ≠ Product specification
Engineering design specification = Product design specification

As the team prepares the EDS, draft sections are circulated among team members for review and comment. Frequent discussions may result as team members resolve specific issues. A team meeting is often convened to discuss its contents. The finished version, however, usually integrates different viewpoints into a common understanding of the design problem. In other words, the process of writing the EDS establishes a team consensus on the important customer and company requirements.

The engineering design specification provides a convenient mechanism to communicate the team's findings to all stakeholders. In some cases, the EDS is presented to upper management in a design review meeting to obtain their approval to continue the product development efforts.

Example

Smart Kitchens, Inc. makes a variety of kitchen appliances for residential use. The company is interested in expanding their product line into electric coffeemakers. The typical Smart Kitchens customer wants a coffeemaker that can brew about 8 cups of hot, delicious coffee. Company management formed a product development team that gathered and interpreted pertinent data. The team then summarized their findings in a preliminary engineering design specification, shown in Tables 3.7–3.8 and Figures 3.8–3.10.

TABLE 3.7 Example Draft Engineering Design Specification for a Coffeemaker

Title: New Coffee Maker for Smart Kitchens, Inc., May 2009

Introduction

- Design problem: home kitchen coffeemaker
- Intended purpose or use: brew and warm coffee

Customer Requirements

Functional performance

- Water should be heated to temperatures between 135° and 175° F
- Brewing time should be less than 6 minutes
- Drip brewing method is required rather than percolation
- Input electricity must be 110–120 volts AC, less than 400 watts

Operating environment

- Residential temperatures 50°–125°F and humidity 10–100%

Economic
- Should have economic life of more than 5 years
- Should not require costly factory servicing

Geometric limitations
- Height, width, and depth less than 15 in. by 10 in. by 10 in.
- Pot must contain a minimum of 48 oz (eight 6-oz cups) of brewed beverage
- Brew chamber should accommodate up to 4 cu. in. of coffee grounds

Maintenance, repair, retirement
- The coffeemaker casing should be easy to clean
- No repairs should be required during economic life
- No special disposal efforts should be required

Reliability, robustness
- No failures should occur during economic life
- Will accommodate variations in water, coffee grounds, supply voltage

Safety
- Will not burn, electrocute or otherwise endanger user

Pollution
- Will not create noise >30 db

Ease of use
- Simple to fill water, add/remove grounds and filter paper
- One switch to turn on/off, with indicator light
- Simple to remove basket and place in dishwasher

Human factors
- No large forces or torques required to operate
- Pot handle to fit 5–95th percentile females and males
- Switch to have obvious mode of operation
- Removable parts should be graspable and not slippery

Appearance
- Color & shape scheme to match current appliance trends
- Surface finish should be smooth to facilitate cleaning

Company Requirements

Marketing
- Retail price should be less than $30

Manufacturing
- Production run quantity is estimated at about 25,000 units
- A beta prototype should be ready for testing in 12 months
- Components must be made with injection-molding processes at current plant

Financial
- Development costs should be paid back in three years

Other
- Production prototype must be UL-approved

Appendices
- Site visit data
- Sales/Marketing data
- House of Quality

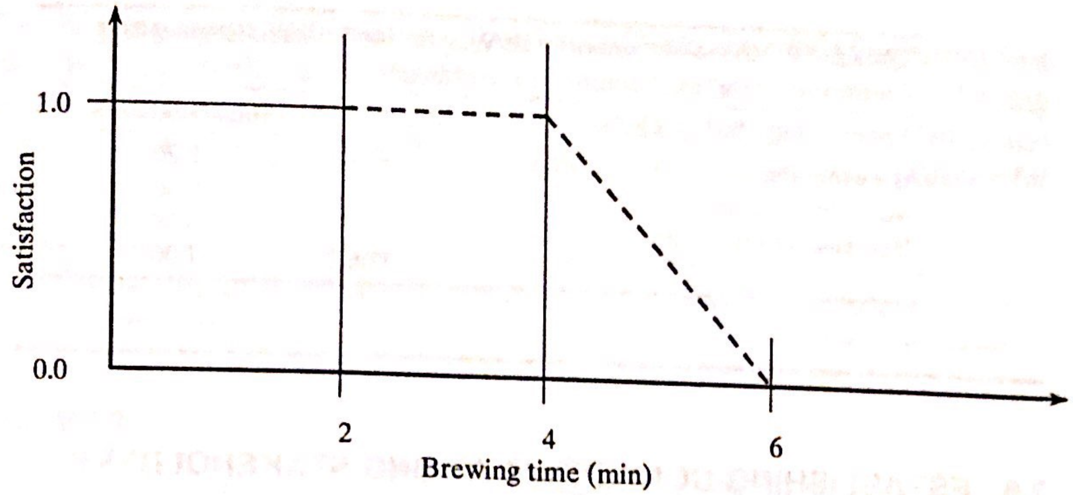


FIGURE 3.8 Customer satisfaction versus brewing time in minutes for example coffeemaker

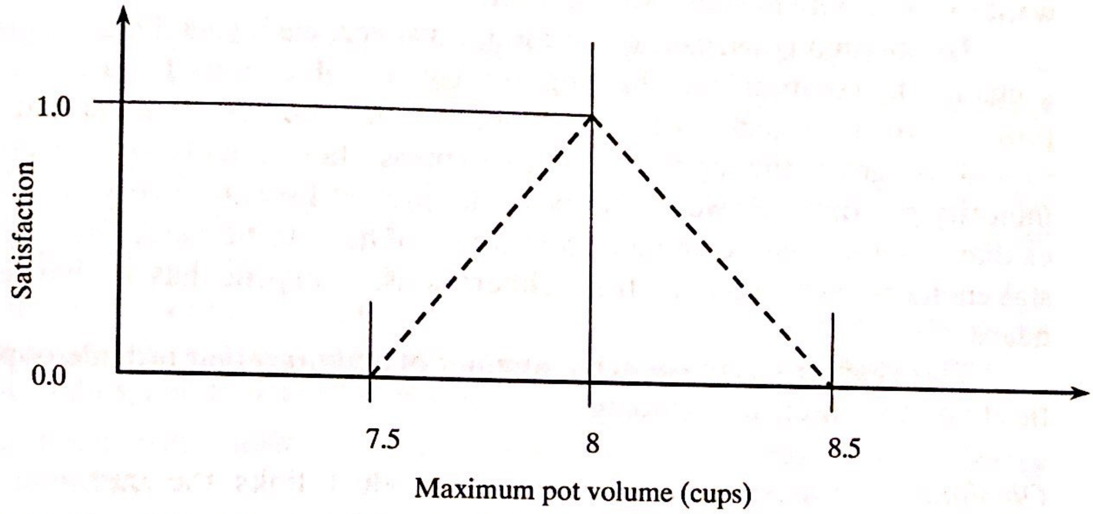


FIGURE 3.9 Customer satisfaction versus maximum pot volume (in 6-oz cups) for example coffeemaker.

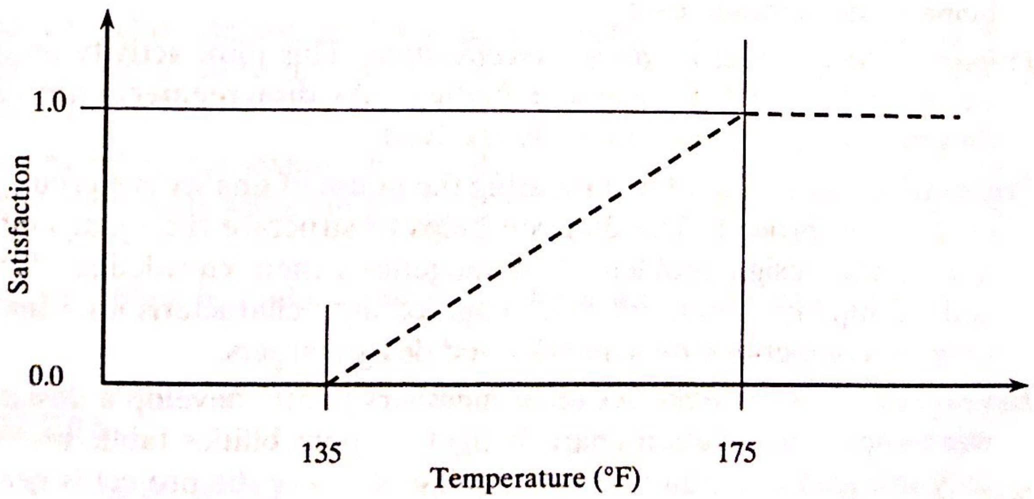


FIGURE 3.10 Customer satisfaction versus beverage brewing temperature (in degrees Fahrenheit) for the example coffeemaker.

TABLE 3.8 Customer Importance Weights for Selected Engineering Characteristics of the Example Coffee Maker.

Engineering Characteristic		Importance Wt.
Brewing time		0.20
Max. Pot volume		0.30
Beverage temperature		0.50
	Total	1.00

3.6 ESTABLISHING CONSENSUS AMONG STAKEHOLDERS

Many people inside and outside of the company, including various layers of management will be involved in engineering design efforts. Most everyone will want to contribute in some way or another.

To obtain a consensus of opinion, however, each stakeholder must have a chance to communicate his support for, or objections to, aspects of the project. Most projects will not proceed unanimously. Critical individuals should be given the opportunity to express their doubts or objections as minority positions. However, to move the project forward, everyone recognizes that at some point, command decisions will have to be made. But, by letting stakeholders participate in the deliberations, everyone has a chance to be heard.

This chapter has presented a number of activities that provide opportunities to build consensus including:

Obtaining a detailed understanding. A product links the customer to the product realization process. To fully understand customer and company requirements, team members from departments such as sales, marketing, engineering, manufacturing, purchasing, and finance need to actively participate and communicate.

Preparing the engineering design specification. This joint activity requires the amalgamation of team member findings. As disagreements are disclosed, they can be openly and rationally resolved.

Preparing a house of quality. Preparing the house of quality is a group problem exploration process. The diagram helps to structure the team's interpretation of the design problem. It homogenizes their knowledge of customer and company requirements, engineering characteristics, importance weights, competitive benchmarks, and design targets.

Developing a project plan. As team members jointly develop a design project workscope, organization chart, budget, responsibilities table, and schedule they will gain a common understanding of where the project is headed and how they will get there. These aspects are presented in Chapter 14.

The *secret* to a successful solution is a sound formulation.

3.7 SUMMARY

- The first step in design problem formulation is to obtain a detailed understanding of the problem, including customer and company requirements, importance weights, engineering characteristics, constraints, and customer satisfaction.
- Engineering characteristics are used to quantify how well an existing product, or future product design, fulfills a given customer or company requirement.
- Customer satisfaction curves illustrate the acceptable upper and lower limits of an engineering characteristic and the incremental satisfaction for a given change in performance.
- A variety of sources are used to gain a better understanding of the problem including: surveys, market studies, literature, focus groups, observation studies, and benchmark studies.
- The engineering design specification summarizes critical product design requirements.
- The house of quality for product planning is a systematic and graphic representation of product design information organized as a matrix of rooms, roof, and basement.
- Quality function deployment is a method that utilizes houses of quality to systematically deploy the "voice of the customer" throughout the whole company.
- Team member consensus can be developed using the concurrent engineering approach while preparing a HoQ for product planning and subsequent EDS.
- Careful problem formulation leads to successful problem solution.

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Badiru, A.B., and P. S. Pulat.1995. *Comprehensive Project Management.* Englewood Cliffs, NJ: Prentice Hall.

Clausing, D. 1994. *Total Quality Development.* New York: ASME Press.

Cohen, L. 1995. *Quality Function Deployment.* Reading, MA: Addison-Wesley.

CHAPTER 4

Concept Design

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Describe design concepts as abstract embodiments of physical principles, materials, and geometry
- Clarify the functional requirements of a design
- Explain and use activity analysis
- Describe and apply function decomposition diagrams
- Systematically generate alternative design concepts
- Analyze concepts for feasibility and/or preliminary performance
- Evaluate concepts using Pugh's methods and the weighted-rating method
- Describe and select various approaches to protect intellectual property

4.1 INTRODUCTION

Concept design is a phase of design when alternative design concepts are generated, evaluated, and selected for further development. But what is a design "concept?" What differentiates one concept from another? A non-engineer would likely define a concept as an idea or thought. A design concept is *not* the same thing. As engineers, we need to be more specific in our use of the term. Let's examine the two examples below to get a better understanding.

First, consider the desired function of stopping a spinning shaft. Three alternative concepts might include a fan brake, a regenerative brake, and a disk brake, as shown in Table 4.1. A fan brake would use aerodynamic/fluid forces. A regenerative brake would use interacting electromagnetic fields. And a disk brake would use surface friction. Each concept uses a different physical principle to achieve the stopping action. The concepts differ in geometric and material aspects also.

Second, consider the required function to fasten sheets of paper. A few alternative concepts are shown in Table 4.2. A paper clip is a loop of solid, elastic material that when separated causes a clamping force. The paper clip is an embodiment that behaves according to the "spring force" physical principle described by Hooke's law.

TABLE 4.1 Alternative Concepts for Slowing and Stopping a Spinning Shaft

Alternative	Physical principle	Abstract embodiment
1	fluid viscosity	fan blade on shaft
2	magnetic field	re-generative brake
3	surface friction	disk and caliper brake

TABLE 4.2 Alternative Concepts for Fastening Sheets of Paper

Alternative	Physical principle	Abstract embodiment
1	spring force	paperclip
2	bent clamp	staple
3	bendable clamp	cotter pin
4	adhesion	glue

As we can readily generalize from the two examples, a **design concept** is an alternative that includes both physical principles and abstract embodiments. But there is more. Design concepts exhibit a number of similarities:

1. concepts work by some physical principle, phenomenon, or principle,
2. physical principles act on some surface or location,
3. concepts exhibit geometric properties, or shapes,
4. concepts are deliberately abstract,
5. concepts imply relative motion of surfaces, or objects, and
6. concepts suggest general material types.

We define a **physical principle** as the means by which some effect is caused, or produced. Physical principles are often described by analytical or empirical relationships that couple the causes and effects, such as Hooke's law $F = k\Delta L$, or Coulomb friction, $F = fN$. A list of some physical principles is given in Table 4.3.

The physical principle acts on a working material. The working material has mechanical, physical, and chemical properties. It may be a solid, liquid, or gas, having inherent mechanical properties such as hardness, ductility, coefficient of friction, modulus of elasticity, and yield strength.

The physical principle acts on the **working geometry** composed of surfaces and motions. A brake disk (rotor), for example, is a flat, circular surface. Physical principles can act at a point, line, area, or volume. For example, air pressure acts on surface area and gravity acts on body volume (i.e. mass). Motions can be rotational, translational, or nonmoving. Motions can also vary with time and magnitude. The successful embodiment of a physical principle on a working geometry in a working material has been defined as a **working principle** (Pahl and Beitz, 1996). The phrase "working principle" is widely used in the European design community.

TABLE 4.3 Representative Physical Principles

Conservation of energy	Archimedes' principle	Ohm's law
Conservation of mass	Bernoulli's law	Ampere's law
Conservation of momentum	Boyle's law	Coulomb's laws of electricity
	Diffusion law	Gauss' law
Newton's laws of motion	Doppler effect	Hall effect
Newton's law of gravitation	Joule-Thompson effect	Photoelectric effect
	Pascal's principle	Photovoltaic effect
Coriolis effect	Siphon effect	Piezoelectric effect
Coulomb friction	Thermal expansion effect	
Euler's buckling law		Heat conduction
Hooke's law	Newton's law of viscosity	Heat convection
Poisson effect/ratio	Newton's law of cooling	Heat radiation

Example

Prepare a sketch of a disc brake concept. Show the disc (rotor) and label the physical principle, working geometry, motion, and material.

When we step on a brake pedal it pushes a rod that compresses hydraulic fluid in the master cylinder. The fluid pressure, approximating 1,000 psi, is transmitted to the brake's caliper piston causing it to expand. The piston forces the brake pads to clamp an annular portion of the rotor surface, causing the frictional braking force.

The solid disc rotates as shown in Figure 4.1 The friction force, F_f, acts on the planar surface that is perpendicular to the axis of rotation.

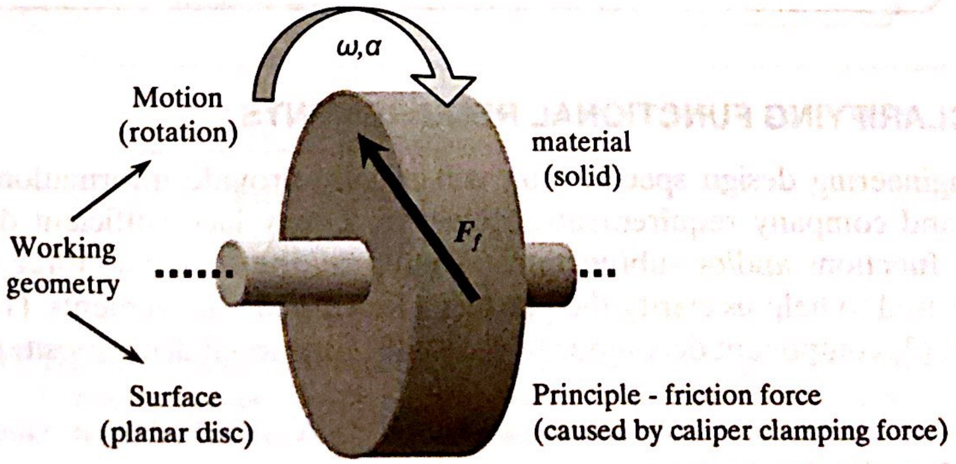


FIGURE 4.1 The disc-brake concept is the abstract embodiment of a physical principle (friction force) acting on the working geometry (rotating planar disc) of a material (solid). Note that at this phase we do not specify precise shapes or sizes.

In concept design we deliberately delay making decisions about specific shapes, configurations, sizes, materials, or manufacturing processes. We do not determine any sizes or configurations. We allow the concept to be an abstract embodiment. For example, we do not select a rotor diameter or a pad thickness for the disk brake; and we do not determine any configuration details for the paper clip such as spiral or circular. In other words, an abstract embodiment will allow us the freedom to generate many alternative configurations, which will be analyzed and evaluated in the configuration design phase, discussed later in the text.

To generate different "concepts" we need only change physical principle, material or geometry. For example, a different friction brake concept design could be generated by changing the working geometry to a "drum." Drum brakes have been in use ever since the horse-drawn wagon. If we are systematic, we can explore different principles, materials and geometry and perhaps synthesize a variety of innovative concept designs.

The concept design phase begins with a review of the engineering design specifications and related documents, and concludes with one or more concepts to be developed further, as shown in Figure 4.2. During concept design we participate in a number of decision-making activities. We clarify functional requirements, generate alternative concepts, and analyze the concepts to determine if they are feasible. We reject infeasible concepts and iterate. Then, we evaluate the feasible concepts to select the best ones for further development. We examine each of these activities in the remaining sections of this chapter.

> A design concept is an abstract embodiment of physical principle, material, and geometry.

4.2 CLARIFYING FUNCTIONAL REQUIREMENTS

The engineering design specification will usually provide information on customer and company requirements. However, it may lack sufficient details on specific functions and/or subfunctions. Therefore, the following three methods may be used to help us clarify the product's functional requirements: (1) activity analysis, (2) component decomposition, and (3) functional decomposition.

4.2.1 Activity Analysis

Activity analysis can be used to learn how the customer will use and ultimately retire the product. Customer activity categories are shown in Table 4.4.

Let's examine the customer activities associated with using and retiring a rechargeable electric shaver, shown in Table 4.5. We often consider just the daily-use pattern, activities 7–15. But maintenance activities 16–18 must also be considered, as well as the setup activities 1–6

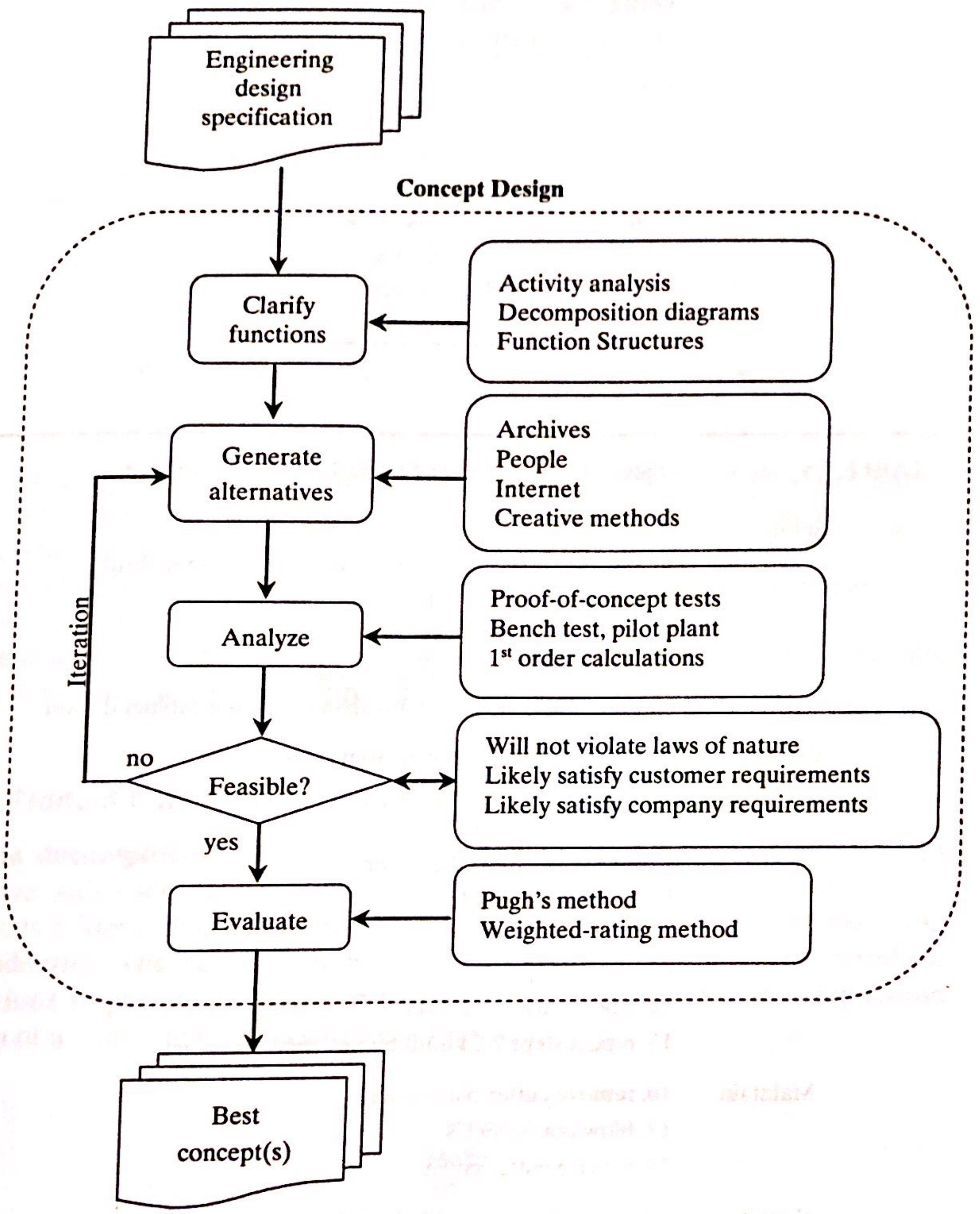


FIGURE 4.2 Decision-making processes and activities during concept design follow the basic sequence of formulate, generate, analyze and evaluate. Note that to be feasible, a candidate concept design should be likely to satisfy "must" customer and company requirements.

We readily see that an activity analysis helps us to understand all the required functions, not just those during daily use. We also learn how the product interacts with the user and the environment. In this case, the shaver is recharged and stored in a drawer. In essence, the activities help resolve customer requirements, or subfunctions that the product must perform in the final design.

TABLE 4.4 Customer Activities Relating to Using and Retiring a Product

Use	set up
	operate
	maintain
	repair
Retire	take down
	disassemble
	recycle
	dispose

TABLE 4.5 Activity Analysis List for Electric Shaver Use and Retirement

Use	Setup	1. open package
		2. examine shaver, cord, travel case, and cleaning brush,
		3. read instruction booklet
		4. fill out warranty card
		5. plug in shaver to charge batteries
		6. put shaver, case, cord, brush in bathroom cabinet drawer
	Operate	7. remove charged shaver from drawer
		8. trim hair
		9. shave face or legs
		10. remove cutter blade cover
		11. brush cutter blade
		12. replace cover
		13. repeat step 5.
		14. store shaver in drawer
		15. repeat steps 7-14 until blades need replacing
	Maintain	16. remove cutter blade cover
		17. blow out particles
		18. replace cutter cover
	Repair	19. install new cutter blade and screen
		20. install new rechargeable batteries
Retire	Dispose	21. throw out shaver and auxiliaries

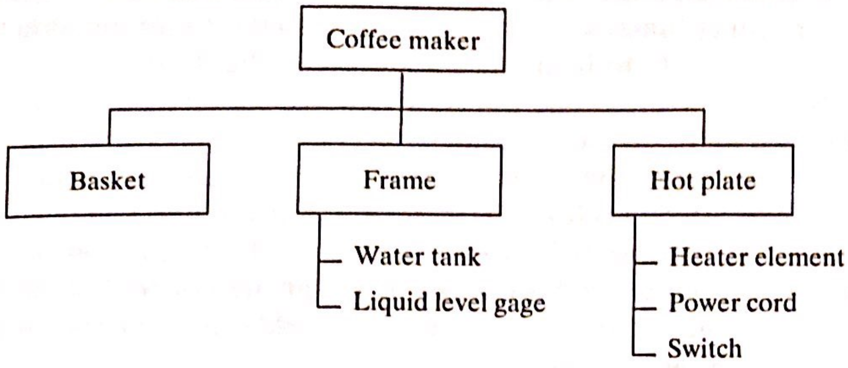


FIGURE 4.3 Component decomposition diagram of a coffee maker.

maker product component decomposition diagrams were presented in Chapter 2. An additional example, that of a coffee maker, is shown in Figure 4.3.

Component decomposition diagrams illustrate the hierarchical structure of component forms, not functions. As we subdivide individual subassemblies into their constituent components, however, we can obtain a better overall understanding of how individual components interact with each other and ultimately contribute to the overall product function.

4.2.3 Product Function Decomposition

Function decomposition subdivides the major functional requirement into its respective subfunctions and sub-subfunctions. The function decomposition diagram is a hierarchical structure of functions, not forms. The diagrams help us to identify whether functions are connected, and where the interface connections might be. For example, let's examine a function decomposition diagram of a coffee maker, as shown in Figure 4.4.

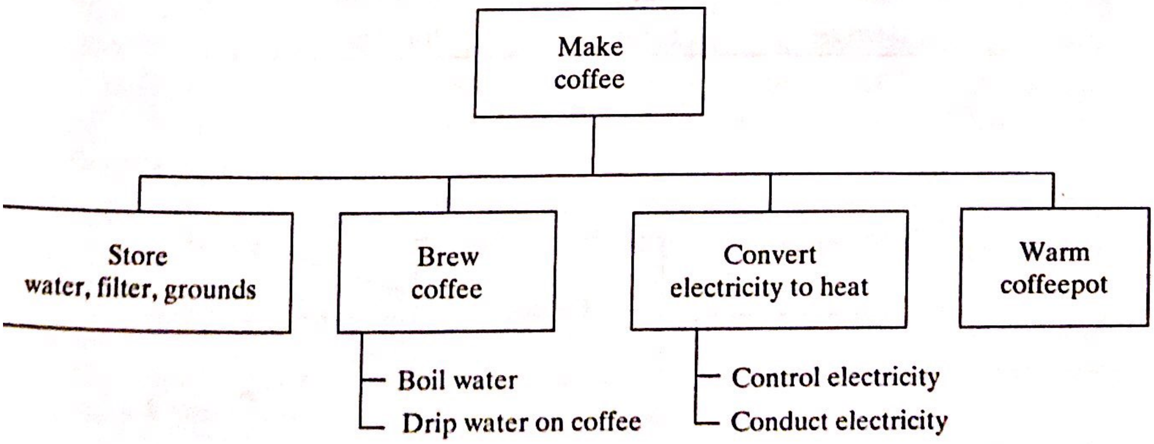


FIGURE 4.4 Function decomposition diagram of a coffee maker.

The first block describes the overall product function, such as make coffee. Then, the product function is further decomposed into subfunction blocks, such as convert electricity to heat and brew coffee. The decomposition is continued so as to successively refine the subfunctions and understand the logical changes in energy, materials, and signal.

Function decomposition diagrams help us separate what the product needs to do (function) versus how it gets done (form). Later, when we investigate alternative concepts, we will explore alternative forms to meet the desired functions. For example, we could choose to warm the pot by hot-air convection rather than a conducting hot plate. Or, we could boil the water in the pot, then pump it into a brewing chamber.

Functions are usually expressed as verbs and act on objects or entities expressed as nouns. In the example above, some verb noun pairs are: brew coffee, warm coffeepot, store water, and convert electricity. A number of other functions are given in Table 4.6.

Noun-objects can be classified into energy, material, and signal categories. When preparing a function decomposition diagram, we should carefully consider how energy, material, and signals are changed or acted on by the function. For example, the cold water is heated, resulting in hot water. Electric energy is transformed to thermal energy. A "switch" signal controls the electric power. The general process is shown in Figure 4.5.

TABLE 4.6 Fundamental Functions

amplify	dissipate	protect
change	fasten	release
channel	heat	rotate
collect	hold	separate
conduct	increase	store
control	join	supply
convert	lift	support
cool	lower	transform
decrease	move	translate

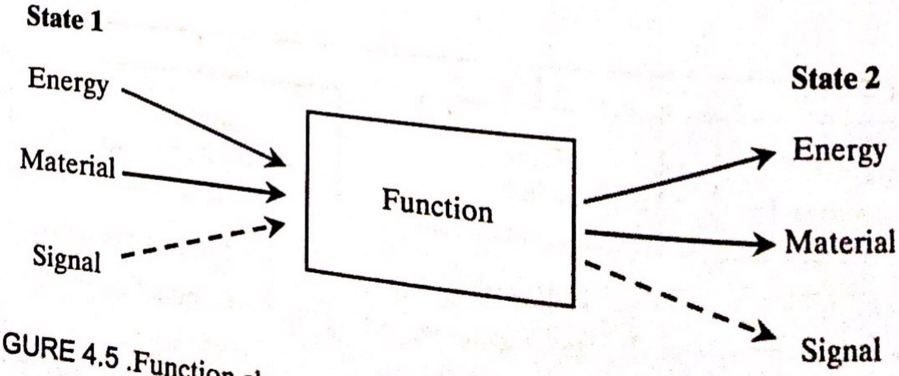


FIGURE 4.5 .Function changes the state of energy, material, and information.

Upon examining the completed function decomposition diagram, the team members may find that they can remove, combine and/or reorganize some sub-functions. For example, they may decide not to warm the pot, that is, remove the subfunction. Other functions might be combined, such as store coffee grounds and brew coffee, as in a basket. During the process of removing, combining, or reorganizing subfunctions, we will likely produce more diagrams. But that is all right. Our goal is to understand the desired product function as best we can.

Detailed function structure diagrams can be created by combining changes in energy, materials, and signals with function decomposition and activity analysis. For further information on function structure diagrams see Hundal (1997), Otto and Wood (2001), and Ullman (1997).

4.3 GENERATING ALTERNATIVE CONCEPTS

To be selective, we need a selection. In other words, if we are to select the best concepts for further development, we need to systematically generate a lot of alternatives. We will be looking for concepts that will potentially satisfy the product subfunctions. Alternative concepts will differ primarily in physical principle, working geometry or material. Note that the process of generating alternatives is sometimes called **synthesis**. Along the way we will investigate archives, talk to people, connect to the Internet, and use creative methods.

Archives. University, public, and corporate libraries should be first on the list of places to look for alternative concepts. In addition to design catalogs, reference handbooks, encyclopedias, and specialized monographs, libraries also maintain collections of periodicals, including technical journals and trade magazines. Some companies also maintain file cabinets full of current and past design information. While most archives are paper-based, other media used include microfiche, microfilm, and computer-based or electronic databases. A systematic search of these sources should trigger a number of alternative concepts.

People. Starting with our co-workers, we can confer, one on one, with people knowledgeable in the field. We might also contact our local university engineering professors. Then, current vendor representatives and professional society acquaintances should be contacted. Finally, we might hire a consultant.

Internet. The Internet should also be searched including: the U.S. Patent Office, Thomas' On-Line Register, vendor Web site catalogs, professional societies, and trade organizations.

Existing Products. If available, competitive products can be purchased and dissected. Although patents may protect the product, the examination often reveals opportunities for new designs.

By researching archives, people, and the Internet, we will find many alternative concepts that have fulfilled previously defined subfunction require-

ments. When we are looking for new solutions, however, we might consider the following innovative methods:

Brainstorming. **Brainstorming** is an iterative group method that takes advantage of team members' diverse skills, experience, and personalities to generate innovative ideas. A group of participants is gathered in a room with an easel or blackboard/whiteboard. After having the "problem" presented, participants suggest ideas that are then transcribed to the easel or board. No criticism of alternatives or ideas is permitted. Wild and crazy ideas are encouraged. The ideas, written on the board, act to stimulate participants. Ideas are transcribed until no new ideas are stimulated. A variant brainstorming uses 3-by-5 cards or post-it notes. Each participant is asked to write down three ideas. The cards are collected and anonymously transcribed to a large whiteboard for everyone to see. After everyone has had a chance to read through the whole list, each member fills out another 3-by-5 card, building on the first set of alternatives. Again, no criticism of ideas is permitted. The cards are again collected, and information transcribed to the larger board. The cycle can be repeated until no more new alternatives are generated. Verbal brainstorming, without cards, is not as good because some members may dominate discussion or telegraph criticism, which can quash creative thinking. In addition the 3-by5 cards can become a permanent record of the meeting.

Method 6-3-5. Method 6-3-5 is a refinement of the brainstorming method, and was developed by Rohrbach (1969). A group of six members gather. Each member writes down three ideas on a sheet of paper. Each sheet of paper is circulated to a neighbor. After reading the ideas, the neighbor writes down three more ideas. The sheets of paper are circulated five times. Variants of this method use different team sizes and number of circulations.

Synectics. **Synectics** is a method that requires the problem solver to view the problem from four perspectives: analogy, fantasy, empathy, and inversion (Gordon, 1961). Viewing similar problems in nature by looking for an **analogy** stimulates idea creation: a tree as an analogy to a structure; a piping network as an analogy to an electrical wiring network. **Fantasy** asks us to imagine the impossible: for example, using an antigravity belt to commute to work. **Empathy** asks us to imagine being a product, and how we would perform each function. **Inversion** asks us to take an "inverted" or reverse point of view, inside versus outside, black versus white, quiet versus noisy, and so on.

Checklists. Companies and individuals have prepared checklists that stimulate creative thinking. For example, Osborn (1957) proposed a checklist of nine starter questions: Substitute? Combine? Adapt? Magnify? Modify? Put to other uses? Eliminate? Rearrange? Reverse? The design team could use a checklist to discuss alternative physical principles, for example.

4.4 DEVELOPING PRODUCT CONCEPTS

During concept design we attempt to generate alternative concepts for each subfunction. A product concept variant, on the other hand, is a development or combination of specific concepts. For example, let's assume that for an arbitrary product, we generate two concepts for subfunction SF_1 and three concepts for subfunction SF_2. We could designate the alternative concepts as C_{ij}, where i represents the subfunction and j represents the alternative concept, resulting in SF_1: $\{C_{11}, C_{12}\}$ and SF_2 : $\{C_{21}, C_{22}, C_{23}\}$. The following six product concept variants are numerically possible:(1) C_{11}, C_{21}; (2) C_{11}, C_{22}; (3) C_{11}, C_{23}; (4) C_{12}, C_{21}; (5) C_{12}, C_{22}; (6) C_{12}, C_{23}.

Sometimes, the combinations are not compatible or realizable, in which case that product concept variant would be eliminated from further consideration. In other cases we may find that a concept can perform or share two functions, like the screwdriver. It can push and turn.

We can list the subfunctions in a column of a matrix, and the alternative concepts for each function in adjacent rows, as shown in Table 4.7. This approach is called a **morphological matrix**. To stimulate alternative combinations, the design team selects one concept from any column, for each function, proceeding down the matrix. The total number of theoretically possible combinations is equal to the product of the number of concepts for each subfunction. In our example we have 2 x 3, or 6 combinations.

TABLE 4.7 Morphological Matrix

		Alternative Concepts				
		1	2	3	...	N
Subfunction	SF_1	C_{11}	C_{12}	C_{13}		C_{1n}
	SF_2	C_{21}	C_{22}	C_{23}		C_{2n}
	SF_3	C_{31}	C_{32}	C_{33}		C_{3n}
	...					
	SF_m	C_{m1}	C_{m2}	C_{m3}		C_{mn}

TABLE 4.8 Morphological matrix for mini-bike subfunctions

Function	Alternative Concepts 1	2	3
Transmit	Chain	Belt	Gearbox
Brake	Disc	Drum	
Steer	Handlebar	Control stick	Fly-by- wire

Combining three alternatives for subfunction 1, two alternatives for subfunction 2, and three alternatives for subfunction 3, we have 3(2)3 = 18 possible combinations. By systematically indexing row and column subscripts we can produce all 18 combinations, as follows:

$$
\begin{array}{lll}
C_{11}, C_{21}, C_{31}, & C_{12}, C_{21}, C_{31}, & C_{13}, C_{21}, C_{31}, \\
C_{11}, C_{21}, C_{32}, & C_{12}, C_{21}, C_{32}, & C_{13}, C_{21}, C_{32}, \\
C_{11}, C_{21}, C_{33}, & C_{12}, C_{21}, C_{33}, & C_{13}, C_{21}, C_{33}, \\
C_{11}, C_{22}, C_{31}, & C_{12}, C_{22}, C_{31}, & C_{13}, C_{22}, C_{31}, \\
C_{11}, C_{22}, C_{32}, & C_{12}, C_{22}, C_{32}, & C_{13}, C_{22}, C_{32}, \\
C_{11}, C_{22}, C_{33} & C_{12}, C_{22}, C_{33}, & C_{13}, C_{22}, C_{33}
\end{array}
$$

Each of the 18 combinations is shown in Table 4.9.The 18 alternatives are then analyzed and evaluated to select the better ones for further development.

TABLE 4.9 Alternative Designs Created by Systematically indexing the Rows and Columns of the Morphological Matrix in Table 4.7

Alternative	Subfunction: Transmit	Brake	Steer
1	Chain	Disc	Handlebar
2	Chain	Disc	Control stick
3	Chain	Disc	Fly-by-wire
4	Chain	Drum	Handlebar
5	Chain	Drum	Control stick
6	Chain	Drum	Fly-by-wire
7	Belt	Disc	Handlebar
8	Belt	Disc	Control stick
9	Belt	Disc	Fly-by-wire
10	Belt	Drum	Handlebar
11	Belt	Drum	Control stick
12	Belt	Drum	Fly-by-wire
13	Gearbox	Disc	Handlebar
14	Gearbox	Disc	Control stick
15	Gearbox	Disc	Fly-by-wire
16	Gearbox	Drum	Handlebar
17	Gearbox	Drum	Control stick
18	Gearbox	Drum	Fly-by-wire

For complicated products the total number of possible combinations can be large. If a subfunction is independent of the others, it can be eliminated from the matrix, and considered separately. For example, the type of radio in an automobile has little or no connection to concept alternatives for drive train.

4.5 ANALYZING ALTERNATIVE CONCEPTS

Not every alternative that we generate will function or be manufacturable. We should screen out, or eliminate, those that are not feasible.

During the concept design phase, we do not have specific information about sizes, configurations, material properties, or manufacturing processes. Each concept variant is characterized only by an abstract embodiments of physical principle, geometry and material.

We can, however, get a rough idea of whether an alternative will function and/or whether we can manufacture it. For example, we can make a few assumptions and calculate a few performance estimates based on simple laws of motion, heat transfer, solid mechanics, and/or thermodynamics. These back-of-the-envelope calculations can rule out "impossible" ideas. We can perform benchtop experiments to see whether a physical principle will work in a specific application. We can confer with manufacturing personnel to confirm the manufacturability of a concept. And we can investigate whether a supporting technology is ready for the production line or should stay in R&D.

The screening criteria should focus on functionality and manufacturability, and should include:

1. Will the concept likely function?
2. Will the concept likely meet the customer's minimum performance requirements? (These are the "musts," not the "shoulds.")
3. Will the concept likely survive the operating environment?
4. Will the concept likely satisfy other critical customer requirements?
5. Will the concept be manufacturable?
6. Will the concept likely satisfy financial and or marketing requirements?

During the analyzing and screening process, we will usually find concept variants that should be eliminated. Or, on the other hand, upon reexamination, some of those to be eliminated might be reconceived, to remove their deficiency. This is an option only if time and resources permit.

4.6 EVALUATING ALTERNATIVE CONCEPTS

Assuming that we have screened out those candidates that were not functional or manufacturable, those remaining can be evaluated to determine which should be developed further.

Two methods commonly used are Pugh's concept selection method and the weighted-rating method.

Pugh's Method for Concept Selection. The concept selection method developed by Pugh (1991) includes the following steps:

1. The team selects evaluation criteria, principally from the engineering design specification and other documents prepared during the formulation phase.
2. A matrix is prepared listing the evaluation criteria in the first column.
3. The concepts are identified in the remaining columns.
4. One concept is selected as the datum concept or reference concept and labeled as datum.
5. The team selects a concept to evaluate. For each criterion the team marks whether the concept is better (+), worse (-), or about the same (S) as the datum.
6. Each of the other concepts is similarly rated, using the same marking system.
7. All the +'s, -'s, and S's are summed and recorded at the bottom of the matrix.

An example matrix for a go-cart transmission is shown in Table 4.10. As the team discusses each entry, it gains a greater understanding of the design problem, the alternative concepts, and the specified requirements. Also, new or revised concepts may originate. These may be added to the matrix for consideration.

When the results are tallied, some concepts may appear as "strong" concepts in that they have more + 's than -'s. For example, it would appear tha the team favors the gears concept, in that there are more + 's and fewer -'s, as compared to the chain concept. However, strong concepts may exhibit a few weaknesses that could be improved upon. Similarly, weak concepts might be strengthened. The method will often indicate the weakest concepts that shoul be eliminated from further development.

TABLE 4.10 Pugh's Concept Selection Method

	Concept Alternative		
Criterion	Gears	V-belts	Chain
high efficiency	+	D	+
high reliability	+	A	+
low maintenance	+	T	S
low cost	-	U	-
light weight	-	M	-
$\Sigma +$	3	NA	2
$\Sigma -$	2	NA	2
ΣS	0	NA	1

The method, as proposed by Pugh, has one drawback, however. Each criterion is assumed to have equal importance. There is no importance weight factored into the evaluation. Modified versions have been proposed that factor in the importance weights. Note that the "+" weights, "-" weights and "S" weights are summed separately to produce the totals. A modified version for the transmission example is shown in Table 4.11.

TABLE 4.11 Modified Pugh's Method

		Concept Alternatives		
Criteria	Importance Wt. (%)	Gears	V-belts	Chain
high efficiency	30	+	D	+
high reliability	25	+	A	+
low maintenance	20	+	T	S
low cost	15	-	U	-
light weight	10	-	M	-
	100			
Σ+		75	NA	55
Σ-		25	NA	25
ΣS		0	NA	20

Weighted Rating Method. The weighted-rating method uses a similar matrix layout as the modified Pugh's method. It is also called the weighted sum method or the Pahl and Beitz method. The method is quite similar and includes the following steps:

1. Team selects evaluation criteria.
2. A matrix is prepared listing the evaluation criteria in the first column.
3. Importance weights are given for the criteria, usually as percentage points, adding to 100.
4. Concepts are identified in columns.
5. Team rates each concept as unsatisfactory, just tolerable, adequate, good, or very good using an ordinal scale such as 0, 1, 2, 3, or 4. Other scales have also been used.
6. Each concept rating is multiplied by its respective weight and summed to produce an overall rating for the concept.

An example weighted rating matrix for a go-cart transmission is shown in Table 4.12. The total weighted rating for the gears is 3.5 and is significantly more than the ratings for the v-belt or chain. Therefore the team would select it for their concept. If the best candidate rating was numerically similar to the other candidates, the team would need to re-discuss and possibly change the ratings.

The process of analyzing and evaluating alternative concepts is naturally subjective, mainly because of the abstractness or fuzziness of the concepts. Some concepts will be obviously infeasible. A few, however, will be identified for further development. Concept design activities also provide an opportunity

Criteria	Importance Weight (%)	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
high efficiency	30	4	1.20	2	0.60	3	0.90
high reliability	25	4	1.00	3	0.75	3	0.75
low maintenance	20	4	0.80	3	0.60	2	0.40
low cost	15	2	0.30	4	0.60	3	0.45
light weight	10	2	0.20	4	0.40	3	0.30
	100	NA	3.50	NA	2.95	NA	2.80

Rating	Value
Unsatisfactory	0
Just tolerable	1
Adequate	2
Good	3
Very Good	4

for the team to obtain a consensus, or common understanding of the important design issues. Communications will play an important role.

4.7 CONCEPT DESIGN PHASE COMMUNICATIONS

A significant amount of information will be produced and processed by the team as concepts are generated, analyzed, and evaluated, including:

- photocopies of archival matter,
- printouts from the Internet,
- vendor catalogs and data sheets,
- preliminary test results
- first-order calculations,
- patent abstracts,
- minutes of meetings,
- concept sketches,
- concept screening sheets,
- concept evaluation matrices, and
- expert interview notes.

Each team member is usually required to maintain a project notebook to organize his personal notes. These notes, especially product ideas and/or sketches, may be used for patent disclosures, as well as trademark and/or copy-right registrations. In addition, the team should establish a central information repository, such as a file cabinet, for the safe keeping of docu-

ments and other information that is pertinent and valuable to the project and company.

Hand sketching is also encouraged during this phase, as compared to CAD drawings. Hand-drawn sketches can quickly communicate form and function. Layout sketches are often used to illustrate the whole idea. Detail and assembly drawings, usually CAD-drawn, are not typically desired until further configuration information becomes available.

The team will also find that centralized computer document files are valuable. Usually available on company file servers, these centralized files can serve as product data archives. Product data management systems can also be utilized as data sources.

Design review meetings minutes should be religiously maintained to record the team's findings as well as their reasoning. The team may find that reviewing these will often resolve misunderstandings. Also, subsequent design teams may find the records to be valuable.

4.8 INTELLECTUAL PROPERTY

Employees act on behalf of the stockholders or owners of a company. We are responsible for the safekeeping of the company's property. Real property, for example, includes assets relating to real estate, like land, buildings, and land improvements such as bridges and parking lots. Personal property is another category of assets; it includes cash, marketable securities, vehicles, and office equipment. To protect these forms of property we use lockable safes, install building fire sprinkler systems and burglar alarms, and purchase insurance contracts.

Intellectual property is another form of property that includes ideas. We typically protect these with trade secrets, contracts, trademarks, trade dress, copyrights, and patents. Protection is especially important during the early stages of product design efforts. First and foremost we must recognize that our company is investing thousands, if not millions of dollars in developing the new product. Automobile companies, for example, will invest millions of dollars in each new model. Second, we need to acknowledge that it is our responsibility, as trustees for the stockholders, to protect product development information. Let's examine the basic types of intellectual property protection.

Trade Secrets. Companies can protect secret intellectual property called **trade secrets** such as formulas, recipes, methods, processes, devices, and/or techniques from unauthorized use by anyone who obtained it by improper means or because of a confidential affiliation. The protection is afforded under most state laws and the Federal Economic Espionage Act of 1996 (ASME, 2001). Examples include the recipes for Coca-Cola, Coors beer, other brand-name food products, in addition to secret processes used to manufacture microcircuits. Two major provisions are that the secret have economic value and that the company maintains its secrecy, including taking steps to:

duced for purposes of news reporting, research, scholarship, or teaching. Works need not be registered to have protection. The three requirements of copyright notice include the © symbol or the word "copyright," the name of the author, and the year that the work was first published. However, unless registered with the Copyright Office (a department of the Library of Congress), authors may not file a law suit in the United States. Registration includes a two-page application, copies of the work, and a modest filing fee. The term of a copyright is the author's life plus 70 years.

Patent. A **patent** is a document granting legal monopoly rights to produce, use, sell, or profit from an invention, process, plant (biological), or design. It is provided by U.S. laws dating back to 1790 and administered by the U.S. Department of Commerce—Patent and Trademark Office.

Utility patents protect inventions such as Xerox copying, Polaroid photography, halogen light bulbs, and countless other machinery. Examples for process patents include polymer processes for Lexan, rayon, and Delrin. A number of conditions exist for a utility-patent invention including that it be (1) new, (2) useful, and (3) unobvious. The invention must also be completely and adequately described in the application. Finally, the invention must not be disclosed to the public more than one year prior to the patent application.

Design patents are granted for ornamental aspects of a product such as shape, configuration, and/or any surface decoration. Examples include the Coke bottle shape, a model of the Statue of Liberty and new fonts.

A U.S. patent is granted only after a thorough review of the inventor's application by the USPTO. Utility and process patents last for 20 years. The design patent lasts for 14 years. The filing fees range from about $500 to $1,100. However, the patenting process may cost $5,000 or more if a lawyer is used to expedite the application process. These costs are typically borne by an employer on behalf of the employee-inventor.

The basic types of intellectual property protection are summarized in Table 4.13.

TABLE 4.13 Summary of Methods to Protect Intellectual Property

	Protects	Length	Application Required	Registration Available	Costs
Trade Secret	formulas, recipes, processes	indefinite	no	no	some
Contract	items specified	length of contract	no	no	>$500
Trademark	graphical symbol or word	20 yrs renewable	no	yes	>350
Copyright	literary, musical or artistic works	author's life +70 yrs	no	yes	>$30
Utility Patent	function, process	20 yrs	yes	yes	>$1,100
Design Patent	appearance	14 yrs	yes	yes	>$500

- identify specific sensitive information,
- notify those having access about its secrecy,
- require employees and visitors to sign confidentiality and nondisclosure agreements,
- restrict access to only those who need to know, and
- compartmentalize a sequence of processes among separate depart- ments, to limit exposure.

A trade secret does not require an application or registration as in patent- ing, and can last an indefinite period of time. However, there is no protec- tion from a third party independently discovering the secret on his own.

Contracts. A **contract** is a written or verbal agreement between two parties, such as between individuals and corporations. Examples include employment contracts having clauses that assign patent rights and copyrights to the em- ployer, and also require the employee to nondisclose, or keep confidential, any proprietary information. Contracts have a finite or specific term, and do not have to be prepared by a lawyer to be valid. However, it is highly rec- ommended and a simple contract may cost as little as $500 in legal fees.

Trademark. A **trademark** is a symbol, design, word, or combination thereof used by a manufacturer to distinguish its products from those of its com- petitors, principally to distinguish its source. Examples include IBM, GE, XEROX, Coke, and Pentium. Protection is provided against others from making, using, or selling products using trademarks under individual state laws and the Federal Trade Act of 1946. Trademark law also protects trade dress. Trade dress is a distinctive, nonfunctional feature (i.e., appearance) that distinguishes a company's goods or services from those of another. Trade dress involves product color, configuration, and packaging. Examples include the packaging for Wonder Bread, the tray configuration for Healthy Choice frozen dinners, and the color scheme of Subway sub shops as well as the Golden Arches, the International House of Pancakes' blue roof, and the Howard Johnson's orange roof. Different from a patent, a trademark is protected from its first commercial use, whether it is registered or not. It need not be registered with the U.S. Patent and Trademark Office (USPTO) or the individual state. However, if registered with the USPTO, protection is afforded in all states by the one application. Registered trademark owners may also display the ® symbol. A trademark has a 20-year life and is indefinitely renewable.

Copyrights. Authors of creative literary, musical, or artistic works are afforded protection under the constitution and the U.S. Copyright Act of 1976. The law provides **copyrights** such that the author can exclusively publish and produce his works and/or sell the rights to his works. Examples include books, sheet music, photos, paintings, sculptures, dramas, sermons, movies, sound recordings, and computer software. The work must be creative, orig- inal, and fixed on paper, canvas, videotape, film, hard drive and/or disk. Under the "fair use" provision, small portions of the work may be repro-

CHAPTER 5

Selecting Materials

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Explain how product function, material, process, and geometry interact
- Describe fundamental material families and classes
- Characterize fundamental mechanical and physical properties
- Screen for acceptable alternative materials
- Develop and use parameters to rate alternative materials

5.1 INTRODUCTION

During the formulation phase of product development we determined the operating environment and the primary functions of the product. Then during conceptual design we selected physical effects and abstract embodiments that would be functional and manufacturable. The abstract embodiments included considerations of working geometries and materials. Finally, even though we did not need to choose specific materials at that time, we made some general assumptions as to their basic properties.

For the brake rotor, for example, we established that the selected material would need to be strong, resist thermal warping, not deflect or deform during use, and not wear out prematurely. From our general knowledge of metals, polymers, ceramics, and composites we assumed that metallic materials would be considered further.

As our product design develops during the configuration and parametric design phases, however, we need to select specific materials for each special-purpose part and for standard parts having optional materials available from suppliers.

During configuration design we will examine product configuration and part configuration. Product configuration includes the spatial arrangement and or connectivity of *components*, whereas part configuration considers the selection and arrangement of *geometric features*.

Parametric design is the last phase of embodiment design. During this phase we want to predict the brake's operating performance, which depends on the specific values of the design variables, such as rotor diameter and

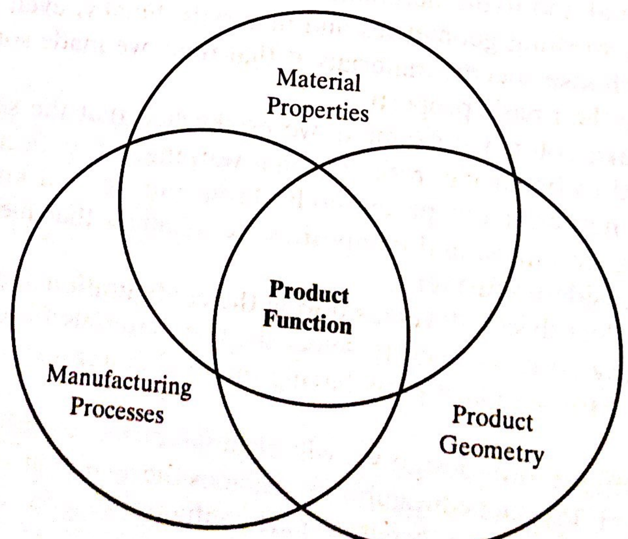
thickness. Therefore, we need to explore specific materials utilizing their properties in our estimates. In the brake rotor design example:

given the following material properties:	*we can estimate:*
coefficient of friction	brake torque
specific heat, thermal conductivity	maximum operating temperature
density	rotor weight
modulus of elasticity	deformations

Then, in detail design we confirm our material choices and their properties, rerunning our calculations with as-delivered material properties, and in so doing, validate our preliminary performance estimates.

Making material selection decisions is difficult, however. A successful product must work and must be manufacturable. For it to work, it must have the right geometry in relation to its function. For example, if the material is too weak, we can often make the shape stouter. However, making a bigger part will likely increase material and manufacturing costs. In fact, as we will see in Chapter 6, "Selecting Manufacturing Processes," some materials and shapes are not compatible with some manufacturing processes. For example we cannot fusion-weld together wood parts. Nor can we hole-punch thermoplastic parts.

Material properties, manufacturing processes, product geometry, and product function are interrelated (Dieter, 2000; Groover, 1996). This interdependence of product function, product geometry, material properties, and manufacturing processes is illustrated in Figure 5.1.



In the remaining sections, we will define some fundamental mechanical properties and physical properties, examine basic material families and classes, examine a method to screen-out inadequate materials, and investigate a method to parametrically optimize material selection.

5.2 MECHANICAL PROPERTIES

A **mechanical property** is a quantity that characterizes the behavior of a material in response to external, or applied, forces. Some of the more frequently used mechanical properties include:

Strength is a measure of the amount of tensile force per unit area that a material can withstand before it fails. If the load is small, a ductile material elastically elongates and then after the load is released the material relaxes without permanent plastic elongation or yielding. We can characterize the strength of materials using a tension test as shown in Figure 5.2. Cylindrical test specimens are subjected to tensile loads in calibrated testing machines. Fracture failure is when the material pulls apart. Brittle materials behave elastically until they fracture. Ductile materials behave elastically; then they yield plastically as the load increases, until fracture. **Stress** is a measure of force intensity per unit area. $\sigma = P/A$ and **Strain** is a measure of relative elongation, $\varepsilon = \Delta L/L$. We can graph these quantities in a stress-versus-strain diagram, as shown in Figure 5.3. A brittle material is shown as the curve OA. A ductile material is shown as curve OEBCD. The curve CE shows that the ductile material elastically recovers some of its plastic deformation.

Yield strength, S_y, is the tensile stress at which a material yields.

Ultimate tensile strength is the largest tensile stress a material can sustain. It is also called **tensile strength** and is denoted as S_{ut}.

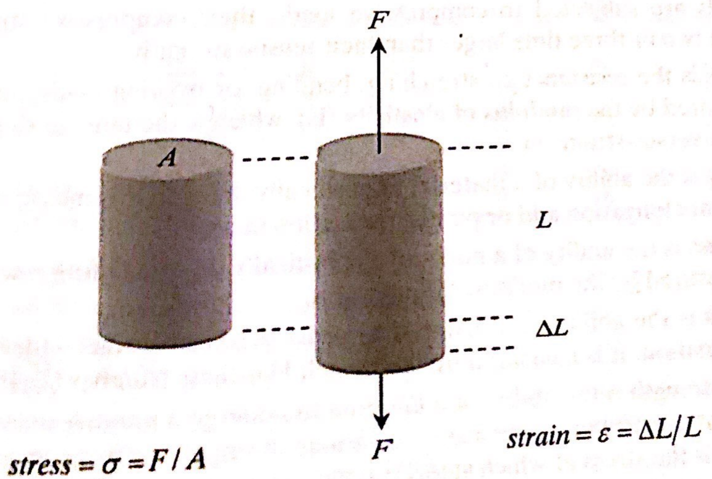


FIGURE 5.2 A tension test uses standard-sized specimens to determine the amount of stress required to produce a given strain in a material.

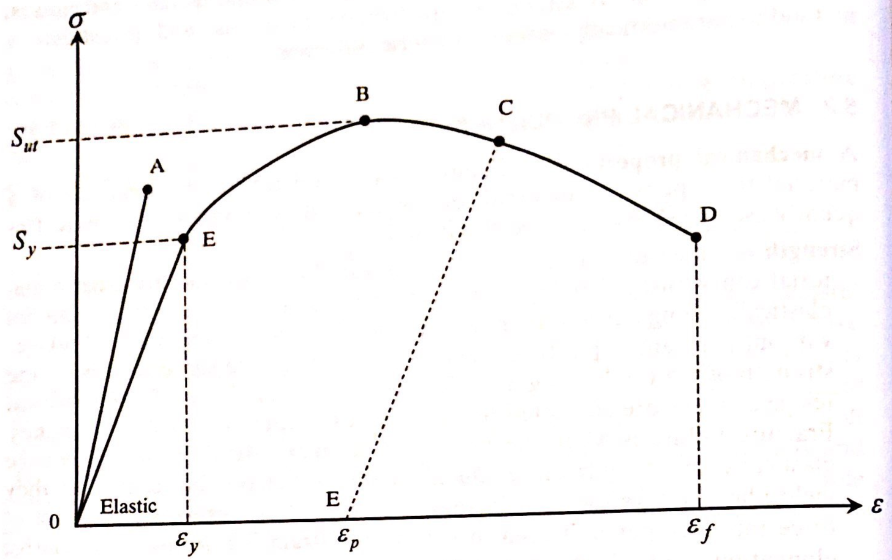


FIGURE 5.3 Stress-versus-strain diagrams for brittle and ductile materials.

Shear strength is the largest stress a material can sustain under torsion before it yields or fractures.

Compressive strength is a measure of the amount of compressive force per unit area that a material can withstand before it fails. Brittle materials are weak in tension compared to ductile materials. However, when brittle materials are subjected to compressive loads, their compressive strength is often two or three time larger than their tensile strength.

Stiffness is the resistance to stretching, bending, or twisting loads. Stiffness is measured by the **modulus of elasticity** (E), which is the tangent slope of the stress-versus-strain curve.

Ductility is the ability of a material to plastically deform. It is measured by the percent elongation and or percent reduction in area.

Toughness is the ability of a material to plastically deform before fracturing. It is measured by the modulus of toughness.

Hardness is the ability of a material to resist localized surface indentation or deformation. It is measured by the Brinell Hardness Number (BHN).

Fatigue strength is the ability of a material to undergo a number of cyclic loads without fracturing. A measure of fatigue strength is the endurance limit, which is the stress at which steels fracture when given a million load cycles.

Creep resistance is the ability of a material to resist stretching while under loads over long time periods at elevated temperatures. It is measured by the

amount of stress that causes rupture within 1,000 hours at the elevated temperature.

Impact strength is the ability of a material to absorb sudden dynamic shocks or impacts without fracturing. The Charpy or Izod test is used to measure impact strength (ft-lbs).

Coefficient of friction is a relative measure of the amount of friction force between two surfaces. It is equal to the ratio of the friction force divided by the force normal to the surface.

Wear coefficient is a measure of the amount of surface removal due to rubbing and sliding.

Mechanical properties are shown for a variety of materials in Table 5.1.

TABLE 5.1 Representative material properties

Class	Member	Heat treat	Elastic modulus Mpsi	Tensile strength kpsi	Yield strength kpsi	Elongation %	Hardness Bhn	Density lb/in^3	Expansion Coeff. 10^{-6} F
Aluminum			10.5					0.1	12
	2014	annealed		27	14	18	45		
	2014	T4		62	42	20	105		
	295	T4		32	16	8.5			
	356	T6		33	24	3.5			
Copper			17.5					0.32	9.4
	C85200			38	13	35			
	C86200			95	48	20			
	C93200			35	18	20			
Magnesium			6.5					0.065	14.5
	AZ91B-F			34	23	3			
Nickel			30					0.3	7
	Hastelloy	as-cast		134	67	52			
	Inconel 600	annealed		96	41	45			
Steel									
	1020	annealed	30	57.3	42.8	36.5	111	0.28	6.7
	4340	annealed	30	108	68.5	22	217	0.28	6.3
	304A	annealed	27.5	83	40	60		0.28	8
Titanium			16.5					0.16	4.9
	Ti-35A			35	25	24			
	Ti-65A			65	55	18			
Zinc			12					0.24	15
	AG40A			41		10	82		
	ZA-12	die cast		57	46	2	117		
Polymers									
	ABS			6		5-20			16
	PTFE			3.4		300			40
	Nylon 6/6			12		60			
	Polypropylene			5		10-20			20
	Polycarbonate			18.5					13
	Polystyrene			13.5					19

5.3 PHYSICAL PROPERTIES

A **physical property** is a quantity that characterizes a material's response to physical phenomena, other than mechanical forces. Physical properties of representative materials are shown in Table 5.2. Some of the more frequently used physical properties include (ASM, 1997):

Density is the amount of matter per unit volume. Density is directly proportional to weight. Two measures for density are mass density and weight density.

Coefficient of thermal expansion is a measure of the amount a material elongates in response to a change in its temperature.

Melting point is the temperature at which a solid changes to a liquid. It is a measure of a material's ability to tolerate elevated temperatures.

Specific heat is the amount of heat required to increase the temperature of a unit mass 1 degree.

Corrosion resistance is the ability of a material to resist oxidation, direct chemical attack, or surface degradation by galvanic currents.

Thermal conductivity is a measure of heat flow across a surface, per unit area, per unit time, per unit of thickness, per degree of temperature difference.

Electrical conductivity is a measure of the ability to conduct electricity. It is equal to the ratio of electric current to the given voltage difference.

5.4 MATERIAL CLASSES

The periodic table lists 103 elements. However, a large number of materials are possible when these are combined in various proportions as compounds.

Much of the effort of materials scientists and engineers focuses on finding the specific recipes that produce compounds that exhibit the right kind of molecular structure, resulting in the right profile of properties.

Engineering materials are separated into a four principal categories: metals, polymers, ceramics, and composites. Other materials include organics such as wood and stone. If we define these categories as "families," similar to Ashby (1999), then each family includes a number of subfamilies that also include classes and subclasses. Let's take a look at the metals family in Figure 5.4.

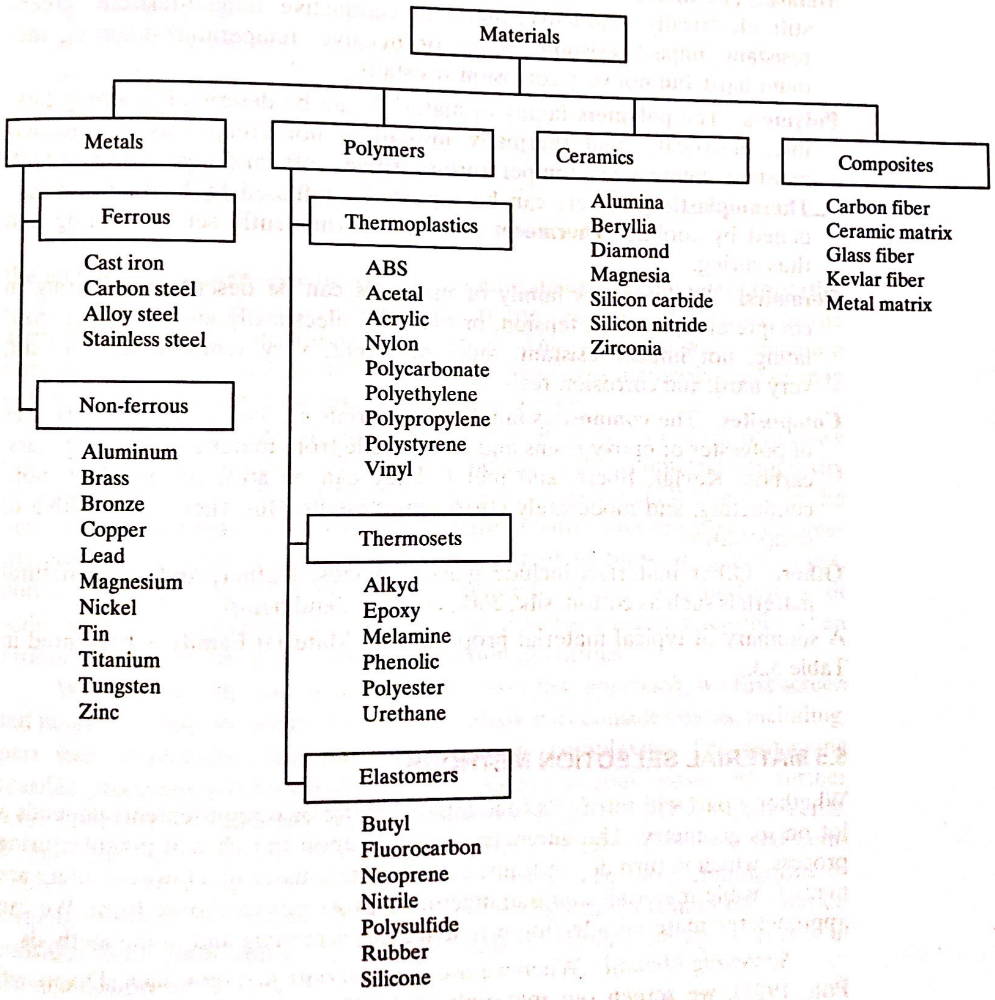


FIGURE 5.4 Material families, subfamilies, and classes

Metals can be divided into ferrous and nonferrous subfamilies. Ferrous metals contain significant amounts of iron. The classes of ferrous metals are cast iron, carbon steel, alloy steel, and stainless steel. Within the carbon steel class, however, there are a couple dozen specific subclasses. The subfamily of thermoplastics, for example, can be divided into classes including: ABS, acetal, acrylic, nylon, polycarbonate, polyethylene, polypropylene, polystyrene, and vinyl. And within each of these are dozens of subclasses that represent the many different compounds or recipes. Note however, that materials in the same family share a number of properties:

Metals. The **metals** family of materials can be described as ductile, strong, stiff, electrically conductive, thermally conductive, fatigue-resistant, creep-resistant, impact-resistant, heavy or massive, temperature-tolerant, medium-hard, but not very corrosion-resistant.

Polymers. The **polymers** family of materials can be described as strong flexible, electrically and thermally insulating, not creep-resistant, impact-resistant, lightweight, temperature-sensitive, soft, and corrosion-resistant. **Thermoplastic** polymers can be repeatedly softened by heating and hardened by cooling. **Thermoset** polymers permanently set by heating and thus curing.

Ceramics. The **ceramics** family of materials can be described as strong in compression, weak in tension, brittle, stiff, electrically and thermally insulating, not impact-resistant, medium-weight, very temperature tolerant, very hard, and corrosion-resistant.

Composites. The **composites** family of materials are heterogeneous mixtures of polyester or epoxy resins and fibers made from materials including glass, carbon, Kevlar, fibers, and metal. They can be stiff, strong, light, non-conducting, and moderately corrosion-resistant. But, they are sensitive to temperature

Other. Other materials include glasses, woods, leather, and other natural materials such as cotton, silk, cork, concrete, and hemp.

A summary of typical material properties by Material Family is presented in Table 5.3.

5.5 MATERIAL SELECTION METHODS

Whether a part will satisfy its functional performance requirements depends a lot on its geometry. The geometry depends upon the chosen manufacturing process, which in turn depends upon the selected material. However, there are many feasible materials and manufacturing processes to choose from. We can approach the material selection problem using screening and rating methods.

Screening Methods. When we use the *materials-first approach* (Dixon and Poli, 1995), we screen out materials that will not satisfy the functional requirements of the part. Namely, we compare application information from

TABLE 5.3 Approximate Material Properties by Material Family

Characteristics	*Metals*	Ceramics	Polymers
Strength	strong	strong – C, weak–T	weak
Elastic strength	very	some	some
Stiffness	very	very	flexible
Ductility	ductile	brittle	—
Hardness	medium	hard	soft
Corrosion resistance	poor	good	excellent
Fatigue resistance	good	—	—
Conductivity (heat/electric)	conductor	insulator	insulator
Creep resistance	good	—	poor
Impact resistance	good	poor	good
Density	high	medium	low
Temperature tolerance	good	super	poor

the engineering design specification to the mechanical and physical properties of material classes. We typically include criteria regarding the nature of the applied loads and the operating environment. This screening will eliminate a number of infeasible material classes. Those remaining materials may or may not be acceptable with some manufacturing processes.

To narrow the feasible processes further, however, we do a secondary screening, considering part information, including: the geometric complexity of the part, the production volume, and part size. As we shall discover in the next chapter, certain shapes are not compatible with some processes. Geometric complexity refers to the type and number of features, including: holes, notches, bosses, rotational symmetry, enclosed cavities, and uniformity of walls and/or cross-sections. Similarly, some processes are not feasible when producing some larger part sizes or production quantities.

When we use the *manufacturing-processes-first approach*, we first screen out manufacturing processes that will not satisfy part considerations, including: part size, production quantities, or geometric complexity. The remaining feasible processes will be compatible with some material classes. We further screen these by comparing material properties to the EDS requirements. Either approach will lead to the same subset of material classes and compatible manufacturing process since we are doing successive eliminations or screenings based on the same criteria. Table 5.4 lists the pertinent information considered for each approach. We will examine manufacturing processes in the next chapter.

TABLE 5.4 Application and Part Information Considered during the Material-First or Process-First Approach to Materials Screening

Material First Approach	Process-First Approach
Application Information	Part Information
1. Applied loads	1. Production volume
magnitude	2. Part size (overall)
cyclic nature (fatigue)	3. Shape capability (features)
rate (slow, impact)	boss/depression 1D
duration (creep)	boss/depression >1D
2. Ambient conditions	Holes
temperature	undercuts (internal/external)
moisture, humidity	uniform walls
chemical liquids/vapors	cross sections (uniform /regular)
sunlight (ultra-violet)	rotational symmetry
3. Conducting (elec/therm)	captured cavities
4. Safety/Legal (FDA, UL, etc)	
5. Cost	

Example

For our rotary-engine powered lawn mower design we decided to use wheels, each consisting of a rubber tire fitted to the outer perimeter of a circular rim. Do a preliminary materials screening for the rim using the materials first approach.

Examining table 5.4 we see that our primary considerations should focus on applied loads, ambient conditions, conductivity, safety/legal and cost.

The typical lawnmower wheel rim is subjected to light constant loads, but can undergo frequent impacts when bumping into objects, for exampple. Ceramics are somewhat brittle and have poor impact resistance, thereby leaving metals, polymers and composites.

Ambient conditions include significant sunlight, moderate air temperatures but high humidity, water egress, and fertilizer chemical attack. Therefore, ferrous and non-ferrous classes would be acceptable, along with ultraviolet resistant polymers, and composites.

Thermal and electrical conductivity is not of significant importance as well as safety or legal issues.

From a cost point of view, carbon steels and aluminum alloys would appear to be least costly.

We will discuss manufacturing processes screening for this example in chapter 6.

Rating/Ranking Methods. To refine our material choices, we can also rate or rank their relative performance using material indices, as proposed by Ashby (1999). Most parts perform a basic mechanical function such as a shaft transmitting a torque or a bracket supporting a force. Functional requirements can be directly related to forces and moments causing tension, compression, beam bending, and column buckling. The performance of the part also depends upon its geometry and its material properties. Incorporating analytical relations from the engineering sciences, performance functions can be obtained in the form:

$$p \le f_1(F)\, f_2(G)\, f_3(M) \tag{5.1}$$

where the performance, p, depends upon the functional requirements, F, the geometric parameters, G, and the material properties, M.

Example

Develop a material index for an inexpensive cylindrical support column.

We wish to minimize total cost C which is a function of the weight W and cost per unit weight C_m. The weight is a function of cross-section area A, length l, and density ρ as

$$C = W\, C_m \tag{5.2}$$

resulting in

$$C = (Al\rho)\, C_m \tag{5.3}$$

Now we need to factor in a constraint that the column does not buckle. Euler's equation for a column whose area moment of inertia I, of length l, recommends that the load P be less than the critical buckling load P_{cr}, as

$$P \le P_{cr} = \frac{\pi^2 EI}{l^2} \tag{5.4}$$

The area moment of inertia for a cylinder is

$$I = A^2 / 4\pi \tag{5.5}$$

We can substitute equation (5.6) and (5.5) into (5.3) obtaining

$$\text{Performance} = 2/\sqrt{\pi}\left\{P^{1/2} l^2 \frac{C_m \rho}{E^{1/2}}\right\} = f_1\left(P^{1/2}\right) f_2\left(l^2\right) f_3\left(\frac{C_m \rho}{E^{1/2}}\right) \tag{5.6}$$

A material index M_I for the inexpensive column can be defined as

$$M_I = 1/f_3 = E^{1/2} / C_m \rho \tag{5.7}$$

Example

Develop a material index for a low-cost bar in tension.

Minimize cost C, given cost per unit weight C_m. The weight is a function of area A, length l, and density ρ as

$$C = (Al\rho)\, C_m \tag{5.8}$$

Factor in a constraint so the bar does not yield due to normal stresses as

$$\frac{F}{A} \le \sigma_f \tag{5.9}$$

The resulting performance equation becomes

$$\text{Performance} = f_1(F)\, f_2(l)\, f_3\left(\frac{C_m \rho}{\sigma_f}\right) \tag{5.10}$$

A material index M_2 for an inexpensive bar can be defined as

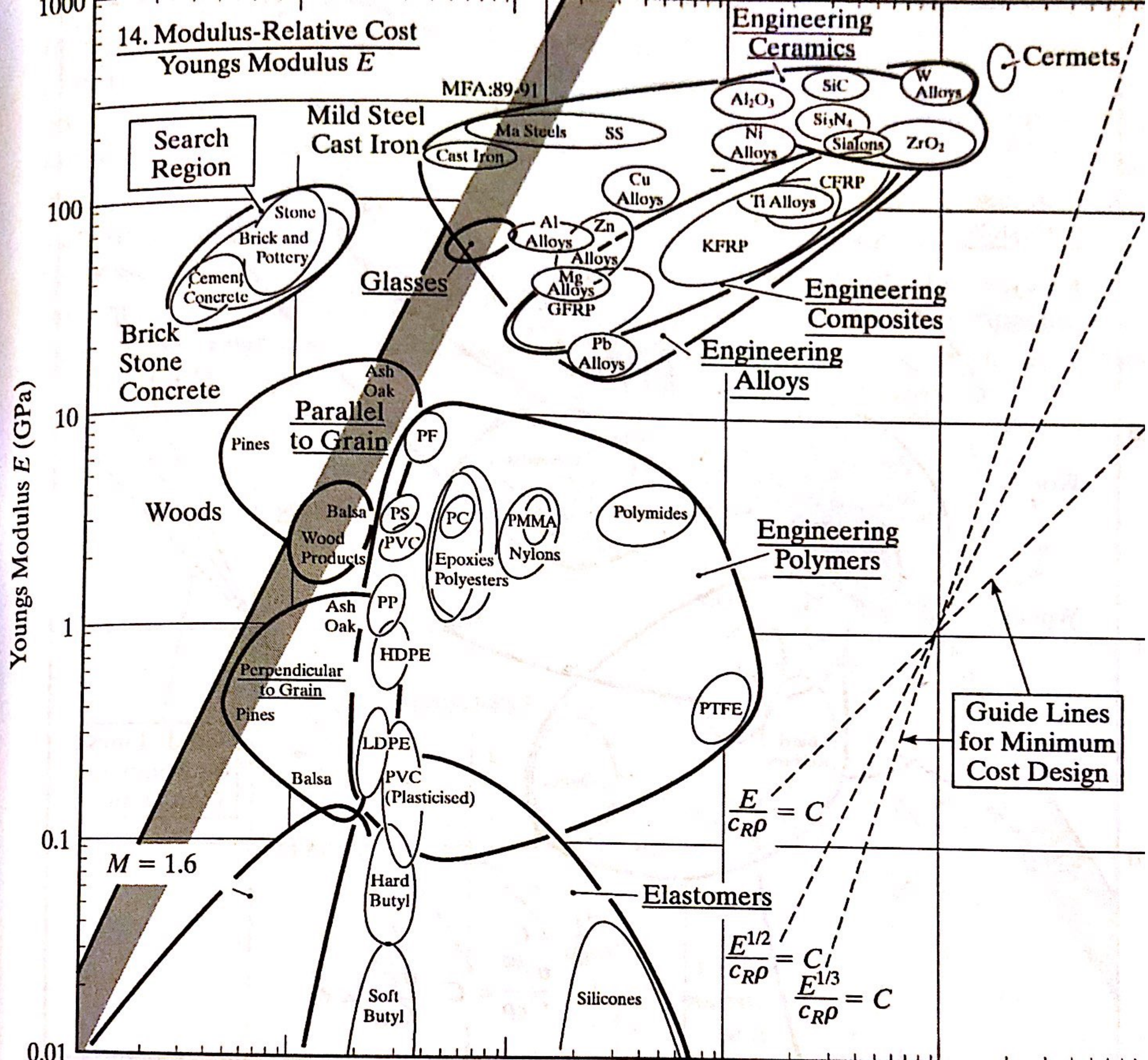
$$M_2 = \sigma_f / C_m \rho \tag{5.11}$$

For example let's compare material A whose strength, density and cost are are 1,000 MPa, 7,800 kg/m^3 and \$1/kg respectively, to material B whose strength, density and cost are 300 Mpa, 2,800 kg/m^3 and \$3/kg.

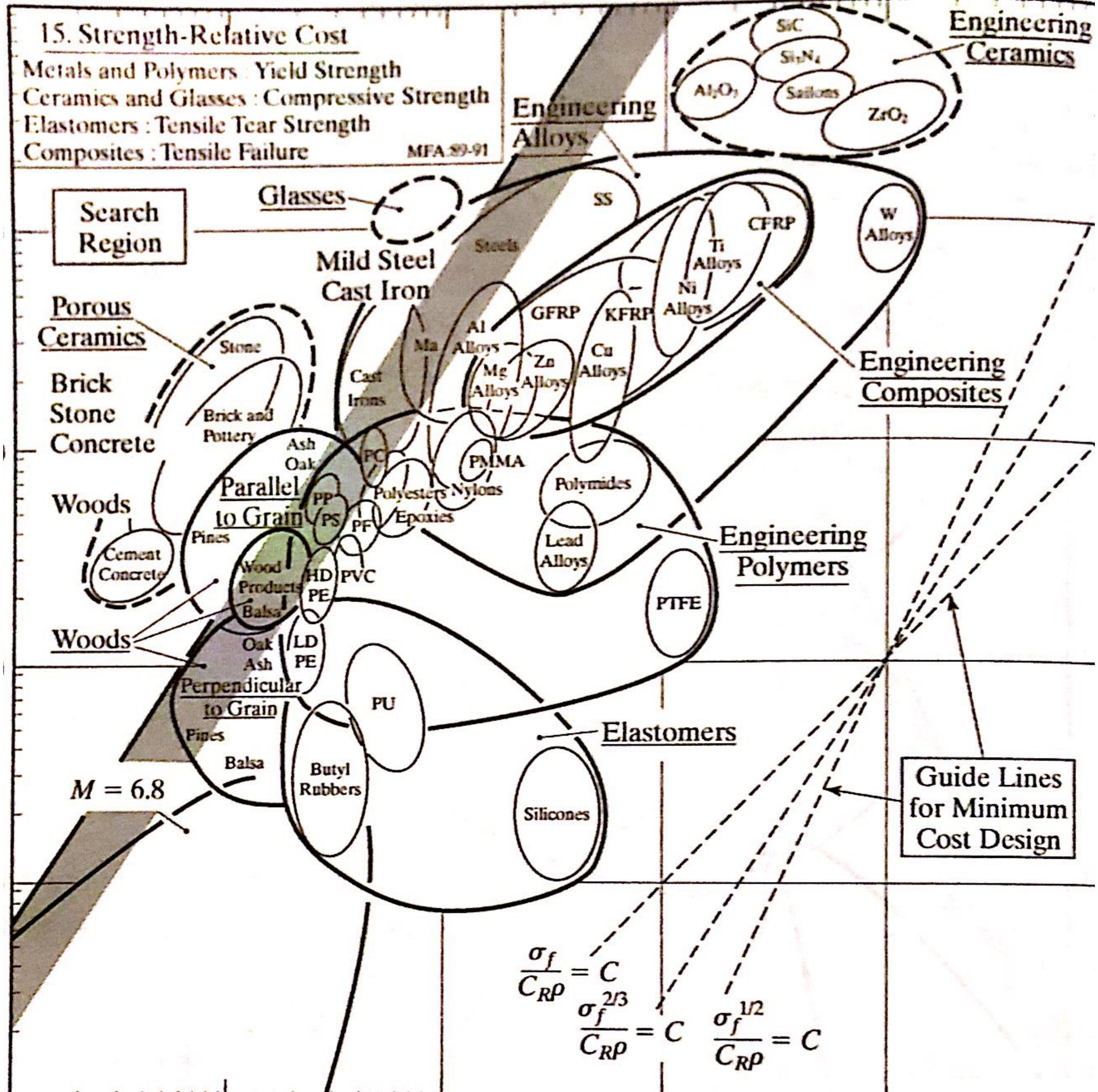
$$M_{2A} = 1000/((1)(7800)) = 0.128 \tag{5.12}$$

$$M_{2B} = 300/((3)(2800)) = 0.036 \tag{5.13}$$

Materials that have higher M_2 index would be stronger and less costly. Therefore, we see that material A is about 3 times more efficient than material B.



14. Modulus-Relative Cost
Youngs Modulus E
MFA:89-91
Youngs Modulus E (GPa)
1000
100
10
1
0.1
0.01
Search Region
Mild Steel
Cast Iron
Ma Steels
SS
Cast Iron
Engineering Ceramics
Al2O3
SiC
W Alloys
Cermets
Si3N4
Ni Alloys
Sialons
ZrO2
CFRP
Ti Alloys
Cu Alloys
KFRP
Stone
Brick and Pottery
Cement
Concrete
Glasses
Al Alloys
Zn Alloys
Mg Alloys
GFRP
Pb Alloys
Engineering Composites
Engineering Alloys
Brick
Stone
Concrete
Ash
Oak
Parallel to Grain
Pines
PF
Woods
Balsa
Wood Products
PS
PVC
PC
PMMA
Nylons
Epoxies
Polyesters
Polymides
Engineering Polymers
Ash
Oak
PP
HDPE
Perpendicular to Grain
Pines
PTFE
LDPE
PVC (Plasticised)
Balsa
Guide Lines for Minimum Cost Design
$\frac{E}{c_R\rho} = C$
$M = 1.6$
Hard Butyl
Elastomers
$\frac{E^{1/2}}{c_R\rho} = C$
$\frac{E^{1/3}}{c_R\rho} = C$
Soft Butyl
Silicones


15. Strength-Relative Cost
Metals and Polymers : Yield Strength
Ceramics and Glasses : Compressive Strength
Elastomers : Tensile Tear Strength
Composites : Tensile Failure
MFA 89-91
Search Region
Glasses
Mild Steel
Cast Iron
Porous Ceramics
Brick
Stone
Concrete
Woods
Woods
Engineering Ceramics
SiC
Si_3N_4
Al_2O_3
Sailons
ZrO_2
Engineering Alloys
SS
Steels
CFRP
W Alloys
Ti Alloys
Ni Alloys
GFRP
KFRP
Al Alloys
Mn
Zn Alloys
Cu Alloys
Mg Alloys
Cast Irons
Stone
Brick and Pottery
Engineering Composites
Ash
Oak
Parallel to Grain
Pines
Cement Concrete
PC
PMMA
PP
PS
PF
Polyesters
Nylons
Epoxies
Polymides
Lead Alloys
Wood Products
Balsa
HD PE
PVC
Engineering Polymers
PTFE
Oak
Ash
LD PE
Perpendicular to Grain
Pines
Balsa
PU
Butyl Rubbers
Elastomers
Silicones
M = 6.8
Guide Lines for Minimum Cost Design
$\frac{\sigma_f}{C_R\rho} = C$
$\frac{\sigma_f^{2/3}}{C_R\rho} = C$
$\frac{\sigma_f^{1/2}}{C_R\rho} = C$

14.2.1 Planning a Project

During the project-planning phase, team members prepare a package of key items collectively called the **project plan**. The amount of effort that a team will spend preparing a project plan usually depends on the extent and type of project. Some design problems require hundreds or thousands of man-hours and take weeks, months, or years to solve such as designing a hydroelectric power plant. On the other hand, a simple selection design problem that is expected to take three man-hours would hardly require a project plan.

A fundamental principle of project management is that those who will work on a project should participate in planning it. Those who will do the work usually know best which specific tasks and deliverables need to be completed. They also know how much time and/or other resources may be needed.

A project plan typically includes:

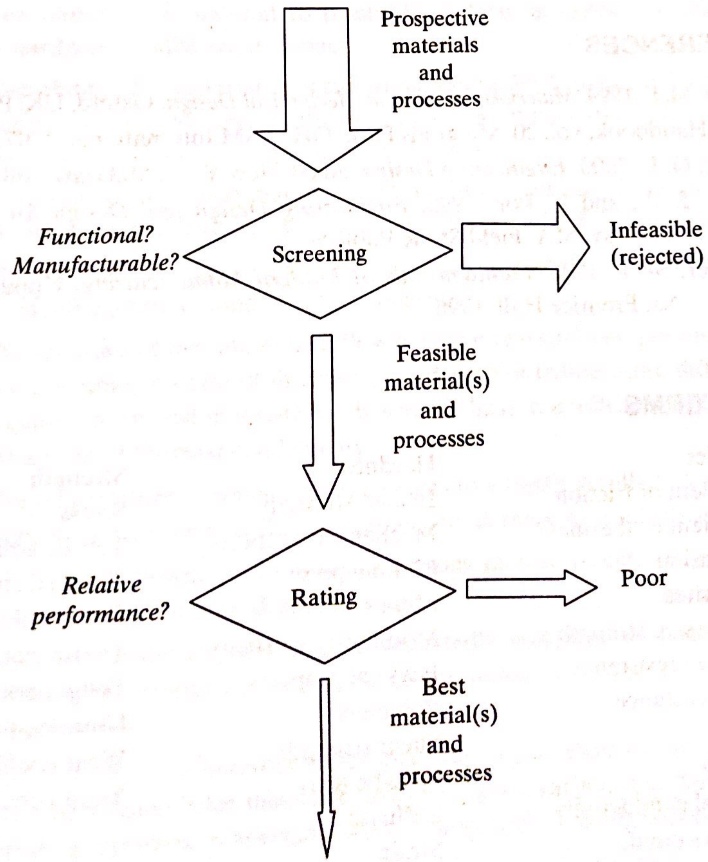
1. Problem statement
2. Mission statement
3. Project objectives
4. Work breakdown structure
5. Scope of work (work scope)
6. Responsibilities table
7. Organization chart
8. Budget
9. Schedule
10. Risk assessment

1. Problem Statement. A problem statement is a simple sentence or two describing a. what the problem is, b. what the desired end state is, c. what currently prevents it, and d. how we know when we have achieved the desired outcome.

2. Mission Statement. A mission statement is a paragraph of two or three sentences that states what we are going to do, for whom, and how we will go about doing it.

3. Project Objectives. To better understand the amount of work in a project we need to develop **project objectives**, which are specific outcomes that we expect to produce. In a design project, for example, we expect to complete a package of "deliverables," including production drawings, prototype test reports, bills of materials, manufacturing process specifications, and performance simulation reports. Project outcomes should be specific as to quantity and quality. Also, outcomes should be realistic in that they consider available time, personnel, and equipment. An example of some project objectives is shown in Table 14.1. By detailing project objectives, we are determining specific "whats" that will be completed, not the "how." The "how" is determined when the work tasks are detailed, as discussed later.

We use screening and rating methods to help us narrow our material choices during the configuration design phase. The general process of screening and rating is shown in Figure 5.7. Using the materials-first approach, or the manufacturing-processes-first approach, we examine the suitability and compatibility of alternative materials and manufacturing processes. The remaining materials and manufacturing processes can then be rated, using the weighted-rating method, discussed in an earlier chapter. As we proceed from screening through evaluation, we see that the number of materials and processes decreases (shown by the decreasing width of the arrow). The resulting "best" materials and manufacturing processes are recommended for detailed analysis and evaluation that occurs in the parametric design phase discussed in Chapter 8.



... evaluation of materials,

CHAPTER 14

Projects, Teamwork, and Ethics

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Develop a project problem and mission statement
- Prepare a project plan, including a work scope, schedule and budget
- Prepare a work breakdown structure diagram and responsibilities table
- Complete an earned-value analysis
- Describe and utilize the elements of successful teamwork
- Describe the forming, storming, norming, and performing stages
- Develop and execute an effective meeting
- Explain and apply the fundamental canons of a code of ethics
- Identify and resolve ethical dilemmas

14.1 INTRODUCTION

The design and manufacture of a product is often accomplished as a project performed by a concurrent engineering team. As the group members participate in the development of a project plan, including a problem statement, mission statement, scope of work, schedule, budget, and responsibilities table, they begin to work as a team. Successful projects can often be traced back to effective teamwork. Similarly, effective teamwork can be traced back to thorough project planning.

We can draw an analogy between project planning and a football team during practice sessions, learning new plays on the board during the "chalk-talk," and then taking the field to drill individual assignments and hone timing. When athletes know what they are supposed to do, and how to do it, they have a good chance at being successful. Similarly, project teams can establish effective teamwork through communication, decision making, collaboration, and self-management.

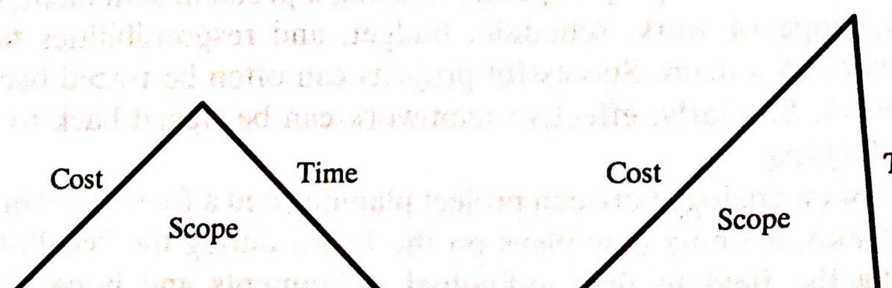
Finally, we will examine the fundamentals of professional ethics and how they relate to our project work tasks and everyday decision making.

14.2 PROJECTS

A **project** is a unique sequence of work tasks, undertaken once, to achieve a specific set of objectives. Design projects, in particular, focus on solving a specific design problem. Other projects include construction or software development. We perform work tasks only once in a project. This aspect helps to distinguish a project from daily work routines. A design engineer may invent a new paper handler for a laser printer as a unique work task. A sales engineer, on the other hand, performs the same routine by contacting a dozen customer prospects as part of his or her normal daily responsibilities.

The four major elements of a project are the scope of work (i.e., set of work tasks to be performed), the cost for labor, materials, and other resources to accomplish the scope, the time allotted, and the quality of the work performed (Lewis, 2002). The four elements are usually interdependent. We can illustrate the coupling of the four elements as three legs and area of a triangle as shown in Figure 14.1. If, for example, the scope of work is expanded to include more work tasks, the costs, quality, or time allotted will be affected. If we expand the scope without changing the cost or time, quality will usually suffer. Whenever a change in one of the four elements needs to be made, a project team would be well advised to consider making revisions to the other three elements.

A project has three main phases: planning, executing, and closing. During planning we determine the what, who, how much, and when. We determine what the work tasks are, who the team members are, which tasks they will complete, how much time, money, and other resources are needed, and when the tasks need to be completed. As we execute our work tasks, we also monitor and control our progress to determine if and when any corrective measures need to be taken. During the closing of a project we reflect and document on our successes and failures, such that we and others in the company can benefit.



Example

Bob Bear, Inc. successfully produces a garden tractor, selling about 50,000 tractors per year. However, the company does not make a snow blower attachment for it. Recognizing that the company has underutilized manufacturing capacity, it would like to develop, manufacture, and sell an attachment that would make better use of the factory and enhance company profits. Write a problem statement and mission statement for a design project to remedy this situation

Problem Statement

Bob Bear, Inc. does not make a snow blower attachment for its garden tractor product. A project is needed to design, prototype, and test a new snow blower attachment that is easy to use, safe, and cost-effective.

Mission Statement

The project team will design, prototype, and test a new snow blower attachment for its existing tractor line. The team will formulate customer and company requirements, develop alternative snow blower concepts, configure snow blower attachments alternatives, establish feasible design variable values, prototype components, and test the final preproduction assembly.

4. Work Breakdown Structure. A work breakdown structure (WBS) is a block diagram that illustrates the major work tasks to be completed during a project. It is a graphical "outline" of sorts. The primary work task categories are shown at the top level, with subordinate tasks underneath each major task. In one glance, the reader gains an overview of the work to be completed. An example is shown in Figure 14.2.

5. Scope of Work. A scope of work is a written detailed list of tasks to be completed during the project. Each level 1 task is subdivided into level 2 tasks. For large projects, level 3 and level 4 task descriptions can be used. Alternatively, the list can be expanded into narrative sentences and paragraphs. Deliverable items, such as progress reports, test reports, physical prototypes, and computer programs, are also mentioned, in addition to the task description. Successful teams use the opportunity to jointly develop the work scope and thereby clarify and resolve potential misunderstandings before the project begins. An example work scope is shown in Table 14.2.

6. Responsibilities Table. The individuals responsible for each task, as well as others who will be assisting, are listed in a project responsibilities table. Those in charge of a task have "R" next to their work time estimate. The table helps to coordinate key team members and those that assist. An example responsibilities table is given in Table 14.3.

7. Organization Chart. An organization chart includes the name and function of each team member. The chart helps to facilitate communications and foster accountability. An example chart for a concurrent engineering design team is shown in Figure 14.3.

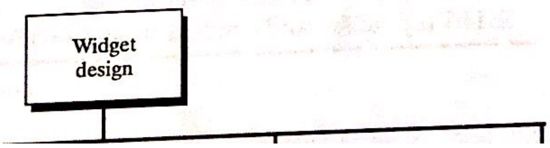


TABLE 14.2 Example Scope of Work for Section 1

1.0 Design problem formulation
- 1.1 Visit site
  - Meet with management/clients to discuss design problem
- 1.2 Contact consumers
  - Make phone calls to determine pros and cons of current unit
  - Set an appointment time to witness existing product in operation
- 1.3 Conduct benchmarking
  - Research existing products that are currently available
  - Contact manufacturers and request brochures
  - Analyze the competition for functionality and performance
- 1.4 Complete QFD/HOQ
  - Determine requirements, engineering characteristics
- 1.5 Determine parameters
  - Define problem definition parameters, design variables
  - Define solution evaluation parameters/performance parameters
- 1.6 Estimate satisfaction levels
  - Estimate satisfaction levels for performance parameter
- 1.7 Prepare engineering design specifications
  - List in-use purposes for the product
  - List customer and company requirements
- 1.8 Finalize scope of work
  - Refine work breakdown structure
- 1.9 Determine schedule
  - Assign a time value to each task
  - Prepare Gantt chart
- 1.10 Prepare budget
  - Determine total number of engineering hours
  - Determine total number of expert faculty hours
  - Sum all hours and material cost
- 1.11 Prepare for and conduct design review meeting with management

TABLE 14.3 Project Responsibilities Table

Project Name: Widget Design   Date: 7/11/04

Task	Smith	Johnson	Tully	Hughs		n-th Person	Hours
1.1	6 R	1	1	2		2	12
1.2	3	3 R	2	3		3	14
1.3	1	2	3	6		6 R	18
1.4	2	1	2 R	2	⇒	4	11
1.5	4	1	1	3 R		5	14
1.6	3	2	2 R	2		2	11
1.7	2	1	2	5 R		3	13
⇓							
m-th task							
Total hours	21	11	13	23		25	93

R - Responsible engineer in-charge

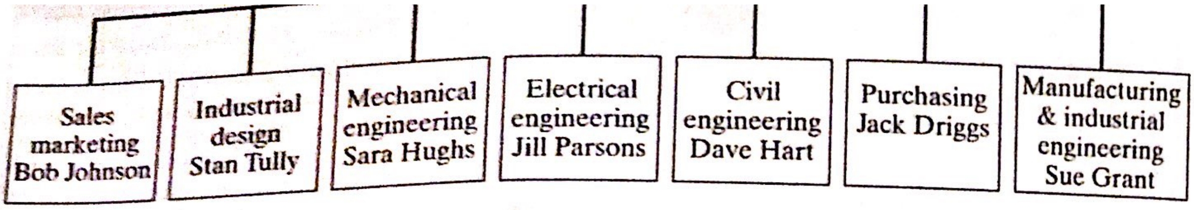


FIGURE 14.3 Example organization chart for design project illustrating the key project personnel. Some charts show other stakeholders, such as management or client personnel.

8. Budget. The planning for each work task is assigned to one or more individuals. They, in turn, estimate the man-hours, and other resources, necessary to complete the assigned task and are summarized in the project budget. An example budget is shown in Table 14.4.

TABLE 14.4 Example Project Budget Listing Major Work Tasks, Time, and Expenses Required to Complete the Project Tasks

Project Name: Snow Blower Attachment Design — Date: 2/7/04

Project Budget

Task	Description	Sr. Engineers	Admin.	Hours	$
1.0	Design Problem Formulation	91	2	93	1900
2.0	Conceptual Design	96	6	102	2160
3.0	Configuration Design	97	8	105	2260
4.0	Parametric Design	160	9	169	3560
5.0	Detail Design	202	10	212	4440
	Total Hours	646	35	681	
	Rate: $/Hour	20	40		
	Total Labor Cost	$ 12,920	$ 1,400		$ 14,320
	Materials/Supplies				$200
			Total Costs:		$ 14,520.00

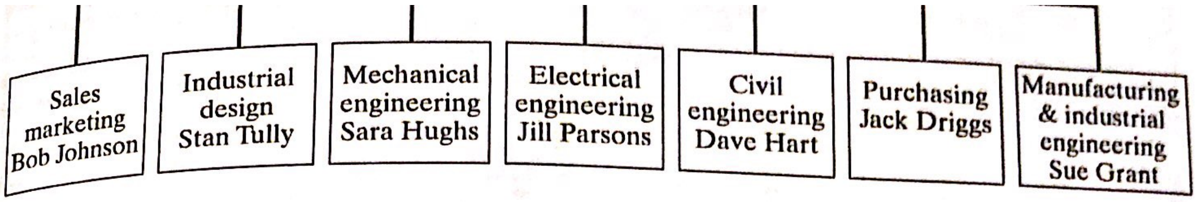


FIGURE 14.3 Example organization chart for design project illustrating the key project personnel. Some charts show other stakeholders, such as management or client personnel.

8. Budget. The planning for each work task is assigned to one or more individuals. They, in turn, estimate the man-hours, and other resources, necessary to complete the assigned task and are summarized in the project budget. An example budget is shown in Table 14.4.

TABLE 14.4 Example Project Budget Listing Major Work Tasks, Time, and Expenses Required to Complete the Project Tasks

Project Name: Snow Blower Attachment Design Date: 2/7/04

Project Budget

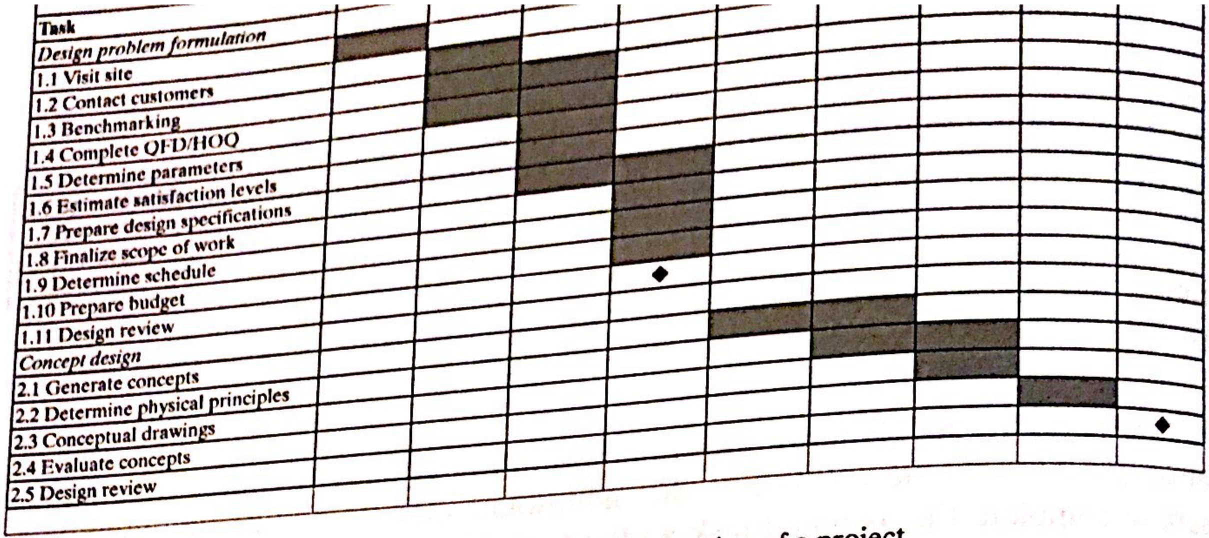


FIGURE 14.4 Example project schedule showing a portion of a project.

The major drawback of the Gantt chart is that succeeding tasks are not "connected" to preceding tasks. It is difficult to determine what effect a delay in a preceding task will have on succeeding tasks and the overall project completion date.

An advanced method, called activity network diagramming, overcomes Gantt chart drawbacks. Project activities are connected by arrows illustrating the network of dependencies. Combinations of parallel and sequential activities are thereby effectively managed. A critical path through the network can be also identified using some simple rules and basic arithmetic. The critical path determines the shortest time to complete the whole network of activities. The program evaluation and review technique (PERT) is an extension of the critical path method and uses quantitative measures to enhance project scheduling. Activity network diagramming is beyond the scope of this book. More information on this method and other aspects of project management can be found in Badiru and Pulat (1995) and Stub et al. (1994).

10. Risk Assessment. The last section of a project plan involves an assessment of the likely risks that face the project and possible contingency plans to overcome such situations. We call this activity risk assessment. First, we determine what risks might exist. Two questions that we might ask are "What is likely to go wrong with the project?" and "What could prevent us from achieving our objectives?" Construction projects, for example face considerable risks, such as building-permit-approval delays, inclement weather, construction-material-delivery delays, and worker strikes. Design projects face risks such as the accidental death or sickness of key personnel, glitches with computer software, delays with fabricating prototypes, testing accidents, and

vendor quote delays. The second aspect of the risk assessment is to consider and recommend a variety of contingency plans. Recognizing key risks in a project and having a couple of ready fallback plans is just smart business.

The project plan is a road map of what the team should be working on, when it should have tasks completed, and how much time and resources to devote to each. Even though the plan is based on estimates that may be under or over budget, or ahead or behind schedule, the plan helps the team to keep under control. Without a plan the team has no idea if it is "on-track" or not. Without a road map the team may not know where it is going, or worse yet, not even reach its destination.

During the project planning phase a significant amount of information is generated and collected. Project notebooks can organize and protect data, analyses, and observations. It behooves each team member to maintain his/her own project notebook. In addition, a team notebook or file cabinet is sometimes used to store originals of key documents. Notebooks and file cabinets should be organized into convenient sections as suggested in Table 14.5.

TABLE 14.5 Example Project Notebook/File Cabinet Sections

Identification sheet
- Project name
- Team member name
- Telephone/e-mail addresses

Design problem formulation
- Engineering design specifications
- Customer notes
- House of quality
- Prior art (library research, Web)/benchmarks

Alternative generation, analyses, and evaluation
- Analysis plan
- Computations, experiments
- Citations for equations, data Spreadsheets
- Sketches, figures, schematics, drawings
- Evaluation plan
- Evaluations/computations
- References/bibliography

Project engineering
- Project meeting notes
- Work breakdown structure
- Scope of work
- Project schedule and updates
- Budget, earned-value analyses
- Risk assessments
- Time sheet—log of work/team meeting hours
- Punch lists of things to be done

Vendor information
- Telephone numbers, addresses
- Phone conversations notes
- Web site printouts
- Product/vendor literature

TABLE 14.6 Example Template for a Design Project Proposal

Design Project Proposal
Cover letter
Title page
Table of contents
Introduction
Problem statement
Mission statement
Engineering design specifications (QFD)
Project objectives
Scope of work
Work breakdown structure (WBS), 2-level diagram
Work scope describing work tasks
Project deliverables associated with tasks
Schedule
Gantt chart
Critical path network diagram
Milestones
Budget
Responsibilities table
Budget
Other resource requirements
Project management
Organization chart of project stakeholders
Project budget and schedule control system
Risk assessment
Design change notice (DCN's) procedure
Appendix
Site visit data

Successful project teams develop comprehensive project plans.

ourselves. We need a way to control the project to make sure our efforts are synchronized and appropriate. Then, we can take corrective measures as needed.

Earned-value analysis is a widely used project control method that compares actual versus budgeted expenses on a period-by period basis. The first step in preparing an earned-value analysis is to calculate the **budgeted cost of work scheduled (BCWS)** for each time period. If, for example, we choose weekly time periods, we would take the total amount budgeted for the work task and allocate it over the weeks that we are scheduled. For example, Table 14.7 shows a project that has three tasks, A, B, and C. Task A is budgeted for $3,000. Let's assume that the project team members will work evenly over the three weeks during which it is scheduled. We therefore enter $1,000 per week for weeks 1, 2, and 3, under the column labeled work task A. Similarly, let's assume our schedule for work task B begins in week 2 and finishes at the end of week 4. Again let's assume that our work efforts are evenly divided among the three weeks. We therefore distribute the $10,500 in $3,500 increments over weeks 2, 3, and 4. We similarly distribute for work task C, which is scheduled to begin on week 3 and end at the end of week 8.

We determine the weekly budget by adding across the columns, arriving at a total budget of $1,000 for the first week, $4,500 for the second week, and so on. The BCWS is shown in Table 14.7 and is an accumulation of the weekly amounts. At any week, we can look at the BCWS column to know what we should have spent in total. The BCWS is a measure of the planned amount of work.

The next step is to determine the **actual cost of work performed (ACWP)**. Fortunately, the accounting department prepares these amounts as weekly expenses. The accounting department tallies payroll, material, and other costs that are actually expended each week as the project continues.

TABLE 14.7 Earned-Value-Analysis Table before the Project Starts (Week #0)

	Earned-Value Analysis						End of Week:		#0
	Work Task								
Week	A	B	C	Weekly	BCWS	BCWP	Schedule Variance	ACWP	Cost Variance
1	1000			1000	1000				
2	1000	3500		4500	5500				
3	1000	3500	2800	7300	12800				
4		3500	2800	6300	19100				
5			2800	2800	21900				
6			2800	2800	24700				
7			2800	2800	27500				
8			2800	2800	30300				
Total	3000	10500	16800	30300					
% Complete	0	0	0						

TABLE 14.8 Earned-Value-Analysis Table as of the End of Week #1

	Earned-Value Analysis						End of Week:		#1
	Work Task								
Week	A	B	C	Weekly	BCWS	BCWP	Schedule Variance	ACWP	Cost Variance
1	1000			1000	1000	750	−250	600	150
2	1000	3500		4500	5500				
3	1000	3500	2800	7300	12800				
4		3500	2800	6300	19100				
5			2800	2800	21900				
6			2800	2800	24700				
7			2800	2800	27500				
8			2800	2800	30300				
Total	3000	10500	16800	30300					
% Complete	25	0	0						
BCWP	750	0	0	750					

These amounts are entered weekly into the weekly column labeled ACWP. Let's assume that the total expenses for the project are \$600. This amount is shown in Table 14.8.

The next step is to calculate the **budgeted cost of work performed (BCWP)** by estimating the **percent complete** for each task and multiplying it by the total task budget amount. The result is a measure of the amount of the budget that was planned for the work actually completed. Assume that at the end of week 1, we have completed about 25 percent of task A; 25 percent of \$3,000 is \$750. We enter this value in the first row of the BCWP column.

Next we compute the schedule variance and the cost variance, for week 1, according to the following formulas:

$$\text{Schedule Variance} = \text{BCWP} - \text{BCWS} \tag{14.1}$$

$$\text{Cost variance} = \text{BCWP} - \text{ACWP} \tag{14.2}$$

$$\text{Schedule variance} = \$750 - \$1{,}000 = \$\,-250$$

$$\text{Cost variance} = \$750 - \$600 = \$150$$

The **schedule variance** is a measure of how much work we accomplished in relation to the amount that was planned. Since we had planned \$1,000 of work, but accomplished only \$750. A negative schedule variance means that we are behind and that we need to make more progress in the coming weeks.

The **cost variance** is a measure of how much we spent in relation to how much we should have spent for the work accomplished. Since we should have spent \$750 to accomplish the amount of work we paid \$600 for, we are under budget by \$150. Since we saved \$150, we might spend some of it on extra help to get caught up to our schedule. A negative cost variance would mean that we overspent for the work performed.

Negative values indicate poor performance, such as behind schedule or over budget, and positive values indicate good performance, such as ahead of schedule or under budget.

Each week we complete the earned-value-analysis spreadsheet to determine if corrective measures are needed. Let's assume that we have been working on the project for seven weeks, and we are finishing the earned-value analysis for the end of week 7, as shown in Table 14.9.

Upon examining the schedule variance we see that the team was behind schedule ever since the project started. Then around week 7 the team began to catch up. Similarly, by examining the cost variance, we see that the team began to overspend around week 4 and especially week 5.

The project manager uses the weekly earned-value analysis results to take corrective actions, such as assigning more or less personnel to the project, or reallocating budget funds among team members or tasks. The schedule variance in week 7 appears to show that the team is getting back on track with regard to the schedule and may finish the project almost on time, but the cost variance indicates they might finish over budget.

A graphical chart of the BCWS, BCWP, and ACWP is shown in Figure 14.5. We see that for weeks 1–4 the BCWP curve was lower than the BCWS, which means that the team was behind schedule. We see that this gap increased, meaning that they got further behind schedule. At week 6 and 7 the gap is narrowing; therefore, they are catching up.

We also see that the ACWP curve is close to the BCWP for the early weeks, meaning that the team was spending their budget in proportion to the work they actually performed. The situation worsened in weeks 4–6 but improved after that.

TABLE 14.9 Earned-Value Analysis for End of Week #7

	Earned-Value Analysis						End of Week:		#7
	Work Task						Schedule		Cost
Week	A	B	C	Weekly	BCWS	BCWP	Variance	ACWP	Variance
1	1000			1000	1000	750	−250	600	150
2	1000	3500		4500	5500	4800	−700	4500	300
3	1000	3500	2800	7300	12800	10800	−2000	11000	−200
4		3500	2800	6300	19100	17300	−1800	18300	−1000
5			2800	2800	21900	18900	−3000	23500	−4600
6			2800	2800	24700	22700	−2000	25600	−2900
7			2800	2800	27500	26955	−545	29355	−2400
8			2800	2800	30300				
Total	3000	10500	16800	30300					
% Complete	97	93	85						
BCWP	2910	9765	14280	26955					

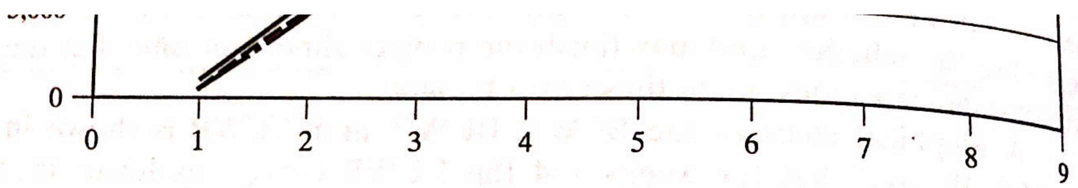


FIGURE 14.5 Earned–value Analysis Graphs of the BCWS, BCWP, and ACWP. The gap between the BCWP and BCWS lines is the schedule variance. The gap between the BCWP and ACWP is the cost variance.

14.2.3 Closing a Project

end

At the conclusion of a project we perform a project review. We reflect back what we learned, what we did well, and what we could have done better. We record and archive these findings for future use. Archival

14.3.1 Elements of Teamwork

Let's examine a well-executed offensive play in football to identify some of the necessary ingredients for teamwork. The quarterback receives the recommended play from the head coach. During the huddle, the quarterback examines the defensive lineup, spots an opportunity to run a different play, and tells the team. As the quarterback calls for the hike, the team simultaneously initiates the new play in a coordinated fashion. Individual team members perform separate roles, but with a common purpose of scoring. Blockers protect the quarterback as he drops back into the pocket for a pass. A halfback sprints forward to a fake a running play. As one receiver sprints from the scrimmage line he sees an opening and adapts his running pattern. The quarterback lofts the football in his direction. The receiver successfully catches the ball and runs toward the goal line with his teammates blocking a path in front of him. Using his well-conditioned running skills he dodges the last tackler and scores a touchdown. Now that was teamwork!

Successful project teams and sports teams exhibit a number of common behaviors which can be classified into four major categories (McGourty and DeMeuse, 2001): communication, decision making, collaboration, and self-management.

Communication Communication is the means by which we exchange information between team members. The quarterback communicated his observation to the offensive line, thereby taking advantage of an opportunity. He also effectively communicated the timing of the hike, preventing an offside penalty. Downfield team members were watching and listening and came to the aid of the receiver.

Principal forms of communication include spoken and written messages. An effective communicator will spend time in preparing better oral presentations, written documents such as e-mails, memoranda, and reports. And an effective communicator will take specific actions to make himself or herself understood.

Listening skills are an important aspect of good communication. The downfield teammates had their “heads up,” watching and listening to the play as it unfolded. Without their “listening” the play might have ended differently. Whether in professional football or business, we can find people who “miss the call” because they are not listening carefully or paying attention.

Listening is an individual skill, something that we have control over, and something that we can improve. Listening guidelines include:

Stop talking. Hear “the play?” Engage in only one discussion at a time.

Show respect. Empathize with the speaker. Show interest in what is being said, respond with appropriate body language, and refrain from interrupting.

Concentrate on what is being said. Do we understand the message completely? Is there something missing?

Stay calm. Keep control of our emotions. React to the ideas or facts not to the speaker presenting them. Try not to jump to any conclusions.

Self-Management Effective teams have members that manage themselves. They monitor their own progress to meet established goals, stay focused on important tasks, use meeting time effectively, solicit constructive feedback on their performance, involve others in all the decision making, and put top priority on getting results.

By improving our collaboration, communication, decision-making and self-management skills we can become better team members. Fifteen teamwork skills are presented in Table 14.10. Informally, we can regularly evaluate our own teamwork skills. We could also ask our fellow team members, from time to time, to provide feedback on our teamwork. More formally, we can use forms: paper, computer, or internet-based, to survey team members and to evaluate ourselves (Eggert, 2008, Loughry et. al. 2007, McGourty and DeMeuse, 2001). The forms are distributed to team members for completion, then collected and forwarded to an independent person, thereby protecting anonymity. A summary report is then prepared and returned to each team member. Frequent feedback and self-reflection are potent tools that help to build teamwork skills.

with 45

TABLE 14.10 Teamwork skills

Collaboration 3	1.	Understands and commits to team goals
	2.	Participates actively in team activities
	3.	Respects individual viewpoints/differences
	4.	Accepts criticism
	5.	Assists other teammates
Communication 1	6.	Listens attentatively to others on team
	7.	Provides constructive feedback
	8.	Communicates clearly and concisely
Decision Making 2	9.	Makes decisions based on facts
	10.	Anticipates problems
	11.	Contributes to meetings
Self-Management 4	12.	Monitors self-progress
	13.	Completes individual tasks thoroughly
	14.	Completes individual tasks on time
	15.	Asks for help when needed

14.3.2 Stages of Team Development

Teamwork develops over time. We don't expect a group of football players to exhibit teamwork the first day of practice. Neither can we expect a business team to do the same. A professional team will practice their skills until they are ready for the game. Unfortunately, few business teams have the same opportunity. Business team members usually develop their skills of communication, decision making, collaboration, and self-management on-the-job.

Ask questions. Take responsibility for some of the communication. Paraphrase the speaker's main points until we understand them. We should first try to understand the speaker before trying to have our views understood.

Decision Making Effective decision making begins with having a clear understanding of the problem. It also involves activities for generating, analyzing, evaluating, and refining alternatives, and then implementing the best one in a timely fashion.

Team decision making takes effort. For example, when we make "individual" decisions we don't necessarily need to communicate with, or understand, others. We can use our own criteria and selection process to decide the best alternative. We rarely have to compromise or consider other options if we don't want to. Team decision making, on the other hand, requires subordinating our own individual desires for the good of the team.

Assuming that the team has gathered the pertinent data and established evaluation criteria and importance weights, they can prepare a weighted rating evaluation to prioritize the alternatives. The final decision, however, comes down to the team making its final selection. Various approaches include a handoff to management, voting, and consensus.

The handoff to management is an abrogation of the team's responsibility to find the best solution for the company. Non-effective teams will pass decisions up the chain of command, especially if the team is concerned about personal retribution. Effective teams will be decisive and recommend action plans for management review and approval.

Voting is a seemingly democratic process, which can lead to some less-than-desirable consequences. If the team decides to use a "unanimous vote required" criterion one team member has the power to veto all choices, such that everyone loses. If the team uses a "majority vote wins" criterion then as the majority wins, the minority loses. Ignoring the minority's issues may put the company at risk.

A **consensus decision** occurs when the team thoughtfully examines all of the issues and agrees upon a course of action that does not compromise any strong convictions of a team member. The approach gives everyone an opportunity to present his case, while recognizing that in some circumstances a "command decision" has to be made. While a team member may not get the choice he favors, at least he knows why, and moreover, agrees that the decision has to be made.

Collaboration Teams that exhibit effective collaboration have members that are committed to the goals of the team, work cooperatively and constructively, actively participate in team activities, and support fellow team members. In our example, the blockers protected the quarterback. And the receiver got blocking help from his teammates when they realized the opportunity for a team score. Collaboration requires subordination of individual desires so that the team can benefit.

One tongue-in-cheek model of team development includes the following sequence of stages:

1. project initiation,
2. wild enthusiasm,
3. disillusionment,
4. chaos,
5. search for the guilty,
6. punishment of the innocent,
7. promotion of the nonparticipants,
8. and finally, definition of the project requirements (Lewis, 2002).

On a more serious note, however, we do find that teams actually experience different stages. Tuckman presented a model describing four stages: forming, storming, norming, and performing (1965).

Forming. At the beginning of a project, participants transition from being individuals to being team members. Somewhat anxiously, members politely interact to learn about the nature of the tasks to be performed, the goals of the project, and the personalities and work styles of fellow members.

Storming. During this stage, members begin to realize the enormity of the project. They recognize differences in individual abilities, personalities, and work styles. Disagreement and conflict may lead some members to retreat from the group to try and "do it alone." Tension, conflict, and scapegoating often occur.

Norming. During this stage members begin to cooperate with each other. They begin to understand and respect individual strengths and weaknesses. They begin to focus on common goals and communicate more openly. They evolve acceptable standards of behavior, or norms, for performing their roles and resolving conflict. And slowly a team spirit begins to emerge.

Performing. During this stage the team is productive and satisfaction is high. Team members share accountability for their actions and are strongly united. Project activities are conducted in an atmosphere of trust and mutual support. Conflicts are resolved openly and effectively as members are comfortable with their

14.3.3 Effective Team Meetings

To be effective, team meetings need to be well planned and efficiently executed. Planning efforts should concentrate on the agenda. Just like a scope of work and in combination with a schedule, an agenda can lay the framework for how a meeting is to proceed. When possible, it should be sent to team members in advance for review and comment. If an agenda is not prepared, we should use the first five minutes or so of a meeting to prepare one.

Agenda An agenda should list the topics to be discussed along with an estimate of time required and the initials of the person coordinating that item of discussion. Topics should be ordered logically. The topics should be designated as a decision item or an announcement. A facilitator may also be designated for each topic. A facilitator keeps the meeting focused and moving. He or she tactfully intervenes when discussions take tangents and prevents anyone from dominating or from being overlooked. The last item of the agenda should be a brief evaluation of the meeting with regard to its effectiveness and plans to improve future meetings.

Effective Execution Having an agenda will enhance any meeting. By executing the agenda, the team will accomplish what it expects to accomplish, in the time it expects to take. The following guidelines, however, are recommended to facilitate its execution.

- *Start on time.* Coming late to a meeting wastes the other participants' time and is disrespectful.
- *Practice effective listening skills.* Understand first, before trying to be understood.
- *Facilitate the facilitator.* Help keep the meeting on time and on topic.
- *Come prepared.* We should never "wing it." If we are presenting an agenda topic, we should be ready for our listeners. It may be the only chance to get our points across.
- *Discuss fact not fiction.* If facts are not available, try to reschedule the topic, such that an informed and factual decision can be made.
- *Take action.* Encourage a consensus decision and move on.
- *Take minutes.* Record key topics, decisions made, and actions to be taken.
- *Draft next agenda.* Before participants leave discuss tentative topics, times, and presenters.
- *Turn off cell phones.* The other meeting participants are honoring us by attending. We should not let any personal calls interrupt the meeting, thereby wasting their time.

14.3.4 Team Rules

We recognize that it is a privilege to be on a team. We also agree to the "rules of the game." Project teams often prepare a list of rules that everyone agrees to and signs. The rules usually require team members to:

- Commit to the goals of team
- Perform assigned tasks completely, accurately and on time
- Respect the contributions of others
- Assist other team members when needed
- Ask for help before we get into trouble
- Follow guidelines for effective meetings
- Actively participate in team deliberations
- Focus on problems not people or personalities
- Constructively resolve conflicts or differences of opinion
- Comment clearly and constructively

14.4 ETHICS AND THE ENGINEERING PROFESSION

As engineering professionals, we make decisions that affect our fellow employers, customers, the public, and the profession. As we make product decisions, for example, we strive to design and manufacture each product so that they are both safe and financially successful for our employer. In some cases, however, a safer product may mean less profits for our company. Should we approve engineering changes that endanger customers, even if it means disappointing our managers? Will our management appreciate and respect the long-term benefits of ethical decision making? Who should we be loyal to? Our employer or the public? Are we obligated to follow a course of action? Do we have a professional responsibility to "do the right thing"?

14.4.1 Code of Ethics

harmed by what other engineers may do, and (5) a code helps to sustain the moral reputation the profession.

The fundamental principles of the ASME code emphasize that if we want to maintain and advance the integrity, honor, and dignity of the profession we should use our knowledge and skill for the enhancement of human welfare. Additionally, that this can be accomplished by being honest, impartial, and faithful to our employers, clients, and the public, and by striving to improve our competence and the prestige, in general, of our profession. Note how the principles embody **ethical values** that we can use to guide our decision making; values such as:

- Integrity—exercising good judgment in the practice of our profession
- Honesty—telling the truth, being sincere
- Fidelity—being loyal to our employer, clients, public, and the profession
- Responsibility—being reliable, dependable, accountable, and trustworthy.

The ten fundamental canons are a set of standards or rules that members of ASME should follow including (ASME, 2009):

1. *Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties.* There is nothing more important than the safety, health, and welfare of the public. We are responsible for conducting safety reviews, and for providing users with information for safe operation. We should not approve designs that could endanger others. Further, if our judgment is overruled we are obligated to inform our clients, employers, or other authorities of the possible consequences. We are also obligated to report other individuals or firms that are in violation.

2. *Engineers shall perform services only in areas of their competence.* We cannot perform engineering work in fields where we are not qualified by education or experience. We have a responsibility to refuse such work.

3. *Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional development of those engineers under their supervision.* We are responsible for keeping up with technology, to know what the current standards of engineering practice are. And we should encourage those under our supervision to do so.

4. *Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest.* We have a responsibility to inform our clients or employers of known conflicts of interest. We should not accept financial or other valuable consideration for specifying materials, equipment, or vendors without disclosure to our clients and employers. We must treat all information received from our clients or employers as confidential. We should not accept outside employment without notifying our employer.

5. *Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.* We should not misrepresent our professional qualifications. We should not embellish or plagiarize technical

reports. We should not injure the professional reputation of other engineers. We should not propose or accept any contracts on a contingency basis such that our judgment might be compromised.

6. *Engineers shall associate only with reputable persons or organizations.* We should not associate with a dishonest or fraudulent party, nor use that party to engage in unethical practices.

7. *Engineers shall issue public statements* only *in an objective and truthful manner.* We should never embellish or misrepresent the facts. We should be objective and present both sides of an argument. We have a responsibility to extend public knowledge and to prevent misunderstandings.

8. *Engineers shall consider environmental impact and sustainable development in the performance of their professional duties.* We must consider the impact of our plans or designs on the environment and provide for the safety, health, and welfare of the public.

9. *Engineers shall not seek ethical sanction against another engineer unless there is good reason to do so under the relevant codes, policies and procedures governing that engineer's ethical conduct.* We should not make unwarranted claims against another engineer.

10. *Engineers who are members of the Society shall endeavor to abide by the Constitution, By-Laws and Policies of the Society, and they shall disclose knowledge of any matter involving another member's alleged violation of this Code of Ethics or the Society's Conflicts of Interest Policy in a prompt, complete and truthful manner to the chair of the Committee on Ethical Standards and Review.* If we want to be a member of the profession, we have to abide by the rules of the profession.

14.4.2 Resolving Ethical Dilemmas

Most employees and employers conduct themselves in an ethical manor. However, there may come a time when we are faced with an unethical situation. How should we go about resolving it? Hopefully we can work it out inside the company. If not, we may need to "blow the whistle" on our employers and go public with our concerns. The following steps are recommended:

1. Obtain the facts of the situation.
2. List the stakeholders who have a vested interest in the outcome.
3. Consider the motivations of the stakeholders.
4. Formulate alternative solutions using codes of ethics, or ethical values.
5. Evaluate the alternatives and reject unethical solutions.
6. Seek assistance from co-workers, supervisors, and ombudsmen.
7. Select the alternative that satisfies the highest ethical values.
8. Implement the selected solution through the chain of command.

9. Monitor the outcome.
10. If unsatisfactory, contact legal counsel, professional society, or the media.

14.5 SUMMARY

- The interdependent elements of a project are the work scope, time, budget, and quality of the work performed.
- A work breakdown structure is an illustration of the basic work tasks.
- Those who will be working on the project should plan it.
- A project schedule indicates the beginning and ending of work tasks.
- Earned-value analysis is a method used to determine whether a project is ahead or behind schedule and under or over budget.
- Teamwork involves communication, decision making, collaboration, and self-management.
- Effective listening skills facilitate being a good communicator.
- Consensus decision making is preferable to voting.
- Teamwork develops through forming, storming, norming, and performing.
- Having a complete agenda is the first step to an effective meeting.
- Professional ethics are standards of conduct based on ethical values.
- A code of ethics provides guidelines of conduct that members must follow.

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